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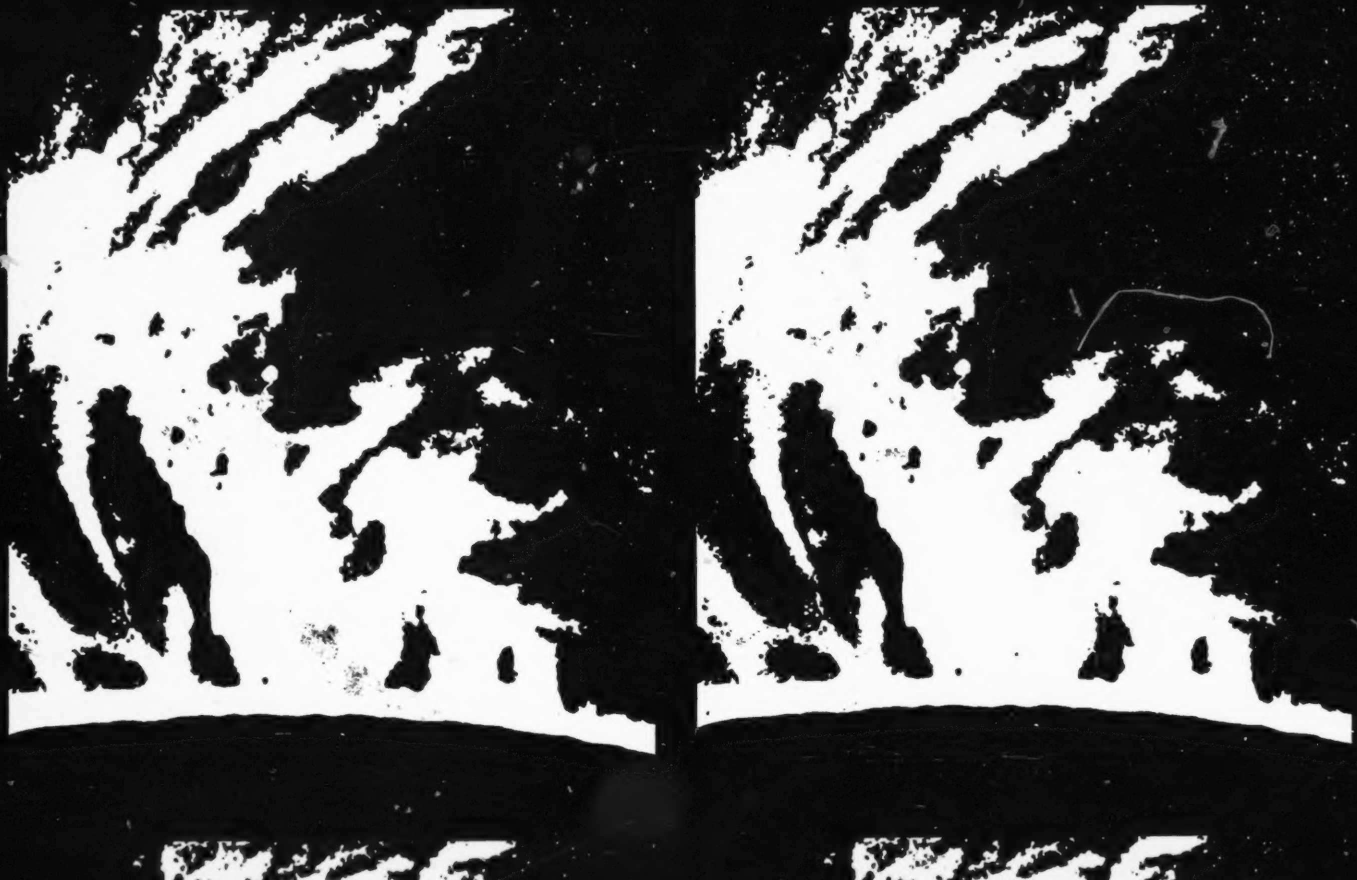
America In Space | The First Decade

Space Physics and Astronomy



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National Aeronautics and Space Administration

America
In
Space:
The
First
Decade

This is one of a series of booklets published on the occasion of the 10th Anniversary of the National Aeronautics and Space Administration.
These publications are not intended to be comprehensive history, nor do they deal with all the facets of NASA's aeronautical and space activities. Rather they are overviews of some important activities, programs and events written for the layman in terms of the several science disciplines.

Each of these subjects is treated in more depth in other NASA publications and in scientific journals.

1 October 1968

Titles in this series include:

I Space Physics and Astronomy
II Exploring the Moon and Planets
III Putting Satellites to Work
IV NASA Spacecraft
V Spacecraft Tracking
VI Linking Man and Spacecraft
VII Man in Space

Others are in preparation. Topics include:

Propulsion
Spacecraft Power
Space Life Sciences
Aeronautics
Space Age By-products
Materials

SPACE PHYSICS AND ASTRONOMY

by William R. Corliss

National Aeronautics and Space Administration, Washington, D.C., 20546

Introduction

In 1958 the National Aeronautics and Space Administration became responsible for developing space science. In that year it took up the work from where balloon and sounding rocket flights had carried it. Four American artificial Earth-satellites had already been put into orbit, and had discovered the Van Allen trapped radiation belt. NASA began immediately with its creation of intensive programs of scientific study. These programs were divided into several disciplines: energetic particles and magnetic fields to study cosmic rays and other energetic particles in space, and to extend magnetic field measurements above the surface of the Earth; ionospheres and radio physics; planetary atmospheres, including that of the Earth; solar physics; astronomy; and cometary physics and interplanetary dust. "Space Physics and Astronomy" describes the progress that has been made in these studies during the first ten years of NASA's existence. It represents one of the avenues selected by the Agency to disseminate the knowledge that it has gained in its programs in keeping with its responsibilities.

John E. Naugle
Associate Administrator for
Space Science and Applications

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Space Physics And Astronomy

Inside The Cocoon

On clear Moonless wintry nights the stars look so close that it is hard to imagine that we live on a cozy planet well insulated from outer space. Three unseen barriers deaden the sights and sounds of the vast, stormy space beyond the Earth. These barriers are the atmosphere, the ionosphere, and a new one discovered by satellites, the magnetosphere. Visible light penetrates these barriers easily; but most meteors, ultraviolet light, long radio waves, and subatomic particles never make it to the Earth's surface. In effect, the Earth is wrapped in a three-ply cocoon.

We need the insulation. Without the atmosphere and magnetosphere to absorb and ward off space radiation, life on Earth might not survive. So potent is space radiation that some scientists now wonder if the mass extinctions of earthly life so obvious in fossil-bearing rocks might be due to temporary losses of our planet's protective magnetic field.

Scientific curiosity about the universe and our place in it is our major stimulus for reaching out beyond the Earth's surface. A few meteorites, cosmic rays, the mysterious auroras, and a thin but steady stream of tantalizing hints about outer space continuously slip through the Earth's insulating layers. To find out more about these phenomena, scientists realized they had to take their instruments to higher altitudes to reduce the absorbing effects of the atmosphere.

In 1643, Torricelli simply climbed a mountain to see what happened to his barometer. Large kites carried instruments even farther. By 1900, balloons had lifted instruments beyond 50,000 feet. Scientific rocketry began in 1929 when Robert H. Goddard installed scientific instruments on one of his rockets. With the rocket, science could, in principle, reach any spot in the solar system. Rockets probed outer space a decade before the first satellites were launched in 1957. Earth satellites turned out to be superb instrument carriers; staying in orbit for years and circling the globe in a matter of hours. They radio back information about our atmosphere and what transpires beyond it.

Scientists found many unexpected things when the first rockets and satellites broke through the atmospheric barrier. Outer space is not an empty vacuum. It seethes with flotsam and jetsam from the solar system. The Sun violently stirs a thin extraterrestrial soup of particles and magnetic fields. Movement and interaction are everywhere.

m = meter
μ = micron = 10^{-6} meters
Å = Angstrom unit = 10^{-10} meters
x = x unit = 10^{-13} meters

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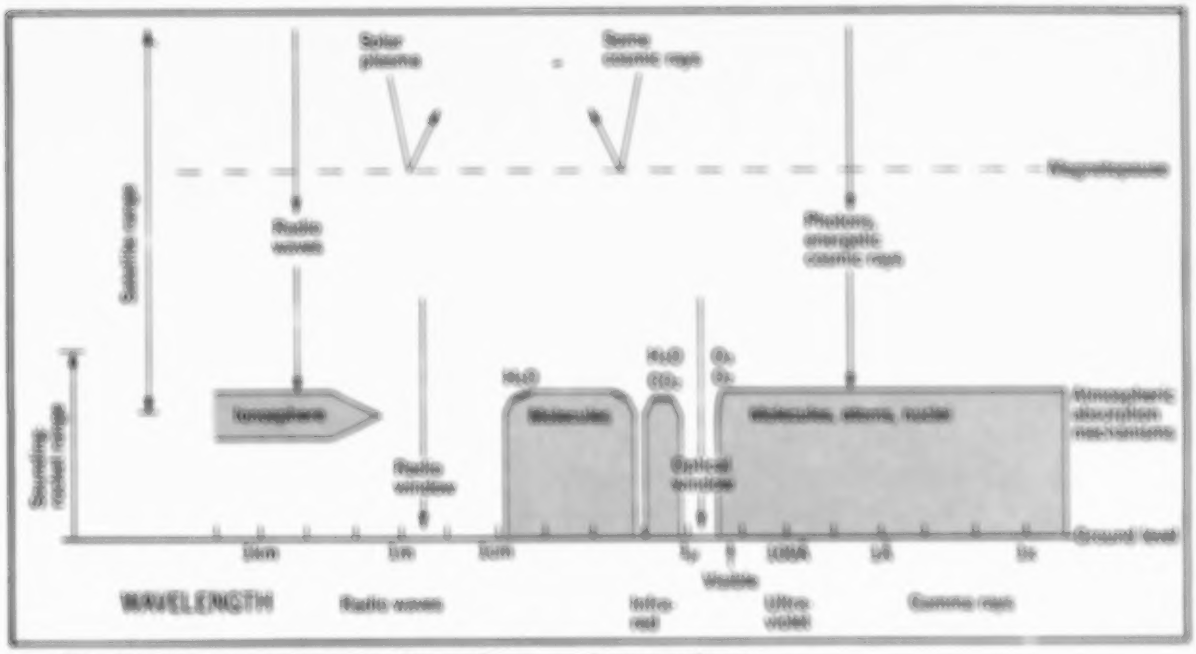

Solar plasma
Some cosmic rays
Magnetopause
Satellite range
Radio waves
Photons, energetic cosmic rays
Sounding rocket range
Ionosphere
Radio window
H_2O
Molecules
H_2O
CO_2
O_3
O_2
Optical window
Molecules, atoms, nuclei
Atmospheric absorption mechanisms
Ground level
1km
1m
1cm
1μ
1000Å
1Å
1x
Visible
WAVELENGTH
Radio waves
Infra-red
Ultra-violet
Gamma rays

1 The Earth's magnetopause, ionosphere, and atmosphere absorb or turn back most of the incoming radiation. Only a small portion of the electromagnetic spectrum reaches the Earth's surface through the windows. Satellites carry instruments in and above these insulating layers.

The past decade has been exciting and rewarding for space science, but the new knowledge and insights have not come easily. And there are many things we still do not understand.

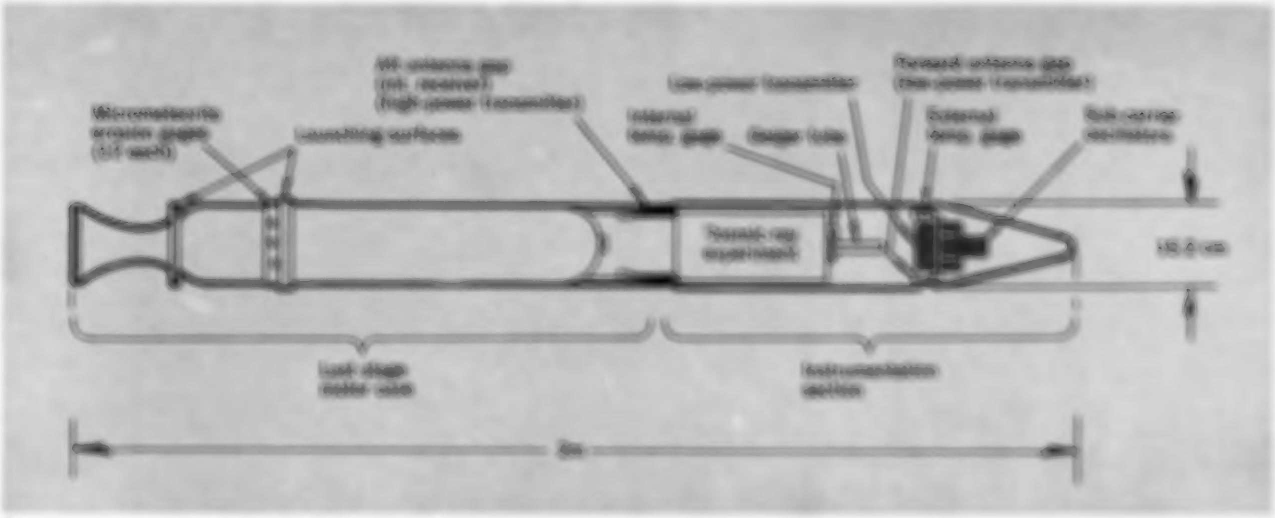
The Great Radiation Belts

Scientists began probing the upper reaches of the atmosphere in 1946 when captured German V–2 rockets arrived at the Army's missile test range at White Sands, New Mexico. Many of these early rockets carried Geiger counters and other radiation detectors to high altitudes. James A. Van Allen, Fred Singer, and other researchers wanted to see how the intensity and nature of cosmic rays varied with altitude and latitude. Like everyone else they were perplexed by the polar auroras (northern lights); perhaps high altitude rockets might find subatomic particles that stimulated the upper atmosphere to emit the eerie greenish light typical of auroras.

One hint came during the summers of 1952 through 1955, when Van Allen's group from the University of Iowa launched rockoons (balloon-launched rockets) from the deck of a Coast Guard cutter in Baffin Bay near the north magnetic pole. Van Allen's Geiger counters detected considerable soft (low energy) radiation at the peaks of the rocket trajectories—some 50 to 60 miles up—where the Earth's magnetic lines of force bend down toward the pole. The results were intriguing. What a boon an artificial satellite would be. It could criss-cross the polar regions north and south several times a day. Van Allen thus became a leading proponent of the embryonic U.S. satellite program and an advocate of placing radiation detectors on the first spacecraft.

Van Allen was successful in his campaign; Explorer I (January 31, 1958) carried a Geiger counter. After the fourth stage of the Jupiter C rocket successfully injected Explorer I into its orbit, the satellite began to climb towards its apogee of nearly 1600 miles. Once in each revolution, every 107 minutes, Explorer I's Geiger counter counted subatomic particles between altitudes of 225 and 1600 miles. As telemetry data were relayed via worldwide tracking stations, Van Allen

2 Explorer III was almost identical to Explorer I. The whole last stage of the Juno launch vehicle went into orbit.



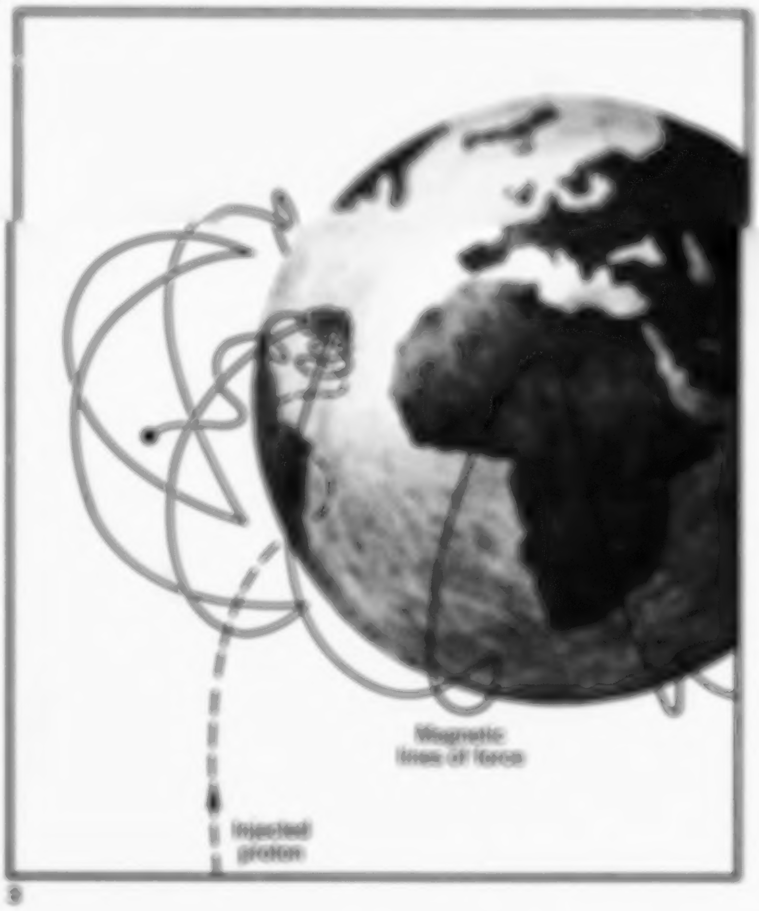
and his associates saw that their Geiger tube did not seem to be working properly. The counting rate first rose as the satellite swung up toward apogee, confirming the existence of the intense soft radiation discovered at lower altitudes in the early 1950s. But as Explorer I passed the 600-mile level, the counting rate abruptly dropped to zero. And it remained zero until the satellite descended below 600 miles. So it went on each orbit. Either the counter was faulty or—just possibly—the counter was saturated; that is, there was so much radiation above 600 miles altitude that the counter couldn't cope with it. This latter surmise was disturbing and completely unexpected by most scientists.

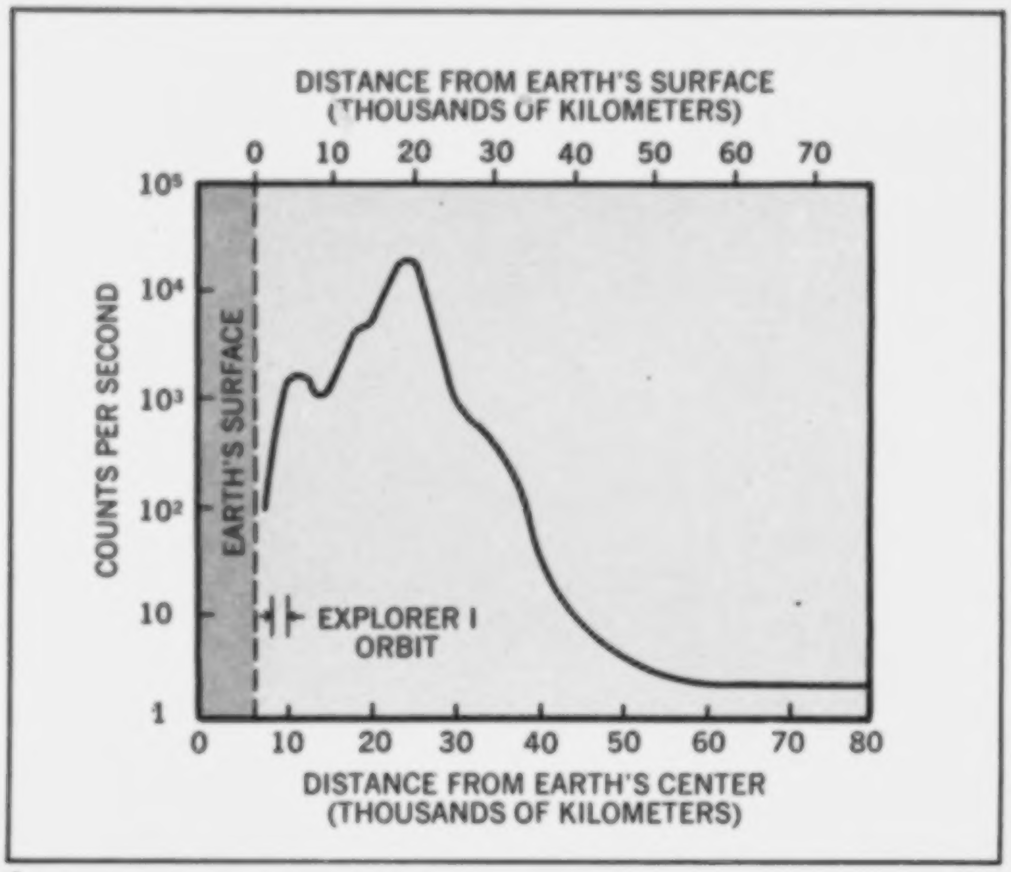
To resolve the question, Explorer II was launched on March 5; but the rocket's fourth stage did not ignite, *and the satellite ended up in the Atlantic.* Explorer III was successful on March 26, 1958. Telemetry showed the same pattern in the Geiger counting rate. No one questioned now that the counter was saturated by unexpected intense radiation.

Why was there a belt of intense radiation above 600 miles? Even before Explorer I, a few brave souls, such as Fred Singer and Nicholas Christofilos, had suggested that electrons and protons might be trapped by the Earth's magnetic field and forced to spiral from pole to pole along the magnetic lines of force. In fact, the Norwegian astrophysicist Carl Störmer had shown the possibility of magnetic trapping as far back as 1904. Nevertheless, most scientists were profoundly surprised by this first great discovery of space science.

Magnetic trapping is easy to visualize. When a charged particle, such as an electron or proton, moves in a magnetic field, it experiences a force perpendicular to both its direction of motion and the magnetic lines of force. Thus, charged particles spiral around the lines of force and follow them corkscrew fashion as they converge on the Earth's magnetic poles. Approaching the polar atmosphere, some particles collide with atoms

3 Magnetic trapping of a charged particle. A proton, perhaps originating in the decay of an albedo neutron, spirals from pole to pole along magnetic lines of force.





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and molecules in the upper atmosphere and get knocked out of the belt; others (in fact, most) are reflected back along the lines of force. The magnetic poles act like magnetic mirrors. The converging magnetic lines of force slow down and reverse the direction of travel of charged particles. The reflected particles spiral from pole to pole, taking only a few seconds for a round trip. The word "trapped" is apt; the particles are released only when they collide with the upper atmosphere.

The belt of radiation surrounding the Earth was quickly named the Van Allen belt. Naming something does not mean we understand it. In 1958, no one knew what kinds of particles occupy the belt or where they come from. More satellite experiments were needed.

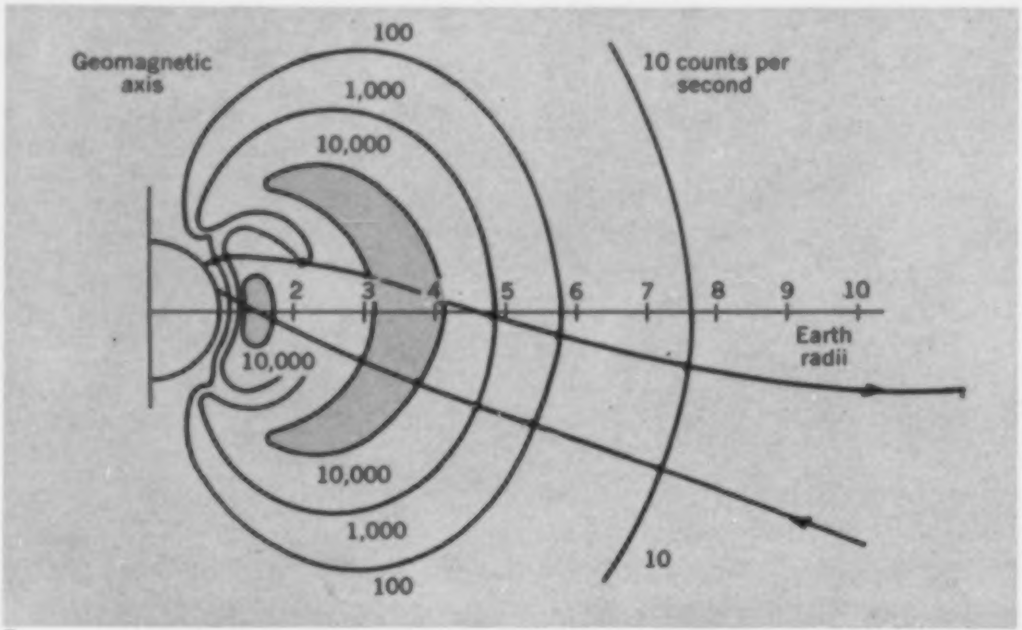
Van Allen quickly readied a payload consisting of two Geiger counters—each surrounded by different amounts of particle shielding—and two scintillation counters, which would respond to particles in a different way from the Geiger tubes. Explorer IV went into orbit on July 26, 1958. It mapped the radiation belt out to about 1400 miles and yielded some information on the energies of the trapped particles. By combining Explorer IV data with that from the deep space probe Pioneer III (launched December 6, 1958), Van Allen was able to draw his famous map showing two concentric belts of charged particles. The map was appealing because some order was made out of the chaos of telemetry data. Nevertheless, the identities of the particles were still unknown, and comparison of data from the various satellites and probes showed that the configuration of the belts probably changed appreciably with time.

Satellite radiation instruments were not yet sophisticated enough in 1958 to identify and sort out all the nuances of the Van Allen belts. It was a high altitude rocket flight with a recoverable payload that first gave science a detailed picture of the denizens of the inner Van Allen belt. Launched in April 1959, an Atlas rocket carried a stack of photographic emulsions into the inner belt. Upon recovering the stack, Stanley Freden and Robert White, at the University of California's Radiation Laboratory, studied the tracks made by the inner belt particles and soon determined that most were very energetic protons.

Where did these high energy protons come from? Theorists had already proposed one explanation for the origin of most of the inner zone protons. When powerful cosmic rays (described later) smash oxygen and nitrogen nuclei in the Earth's atmosphere, neutrons are emitted in the ensuing nuclear reactions. Some of these neutrons head toward outer space and pass through the Van Allen belts in the process. Being electrically neutral, the neutrons would

4 *The radiation counter on Pioneer III recorded two radiation peaks as it penetrated the Van Allen belts on its flight toward the Moon on December 6, 1958. Explorer I had repeatedly grazed the lower edge of the belts.*

5 *The famous kidney-shaped picture of the radiation belts drawn by Van Allen after the flight of Pioneer III. In modern maps, the two belts are not so well defined.*



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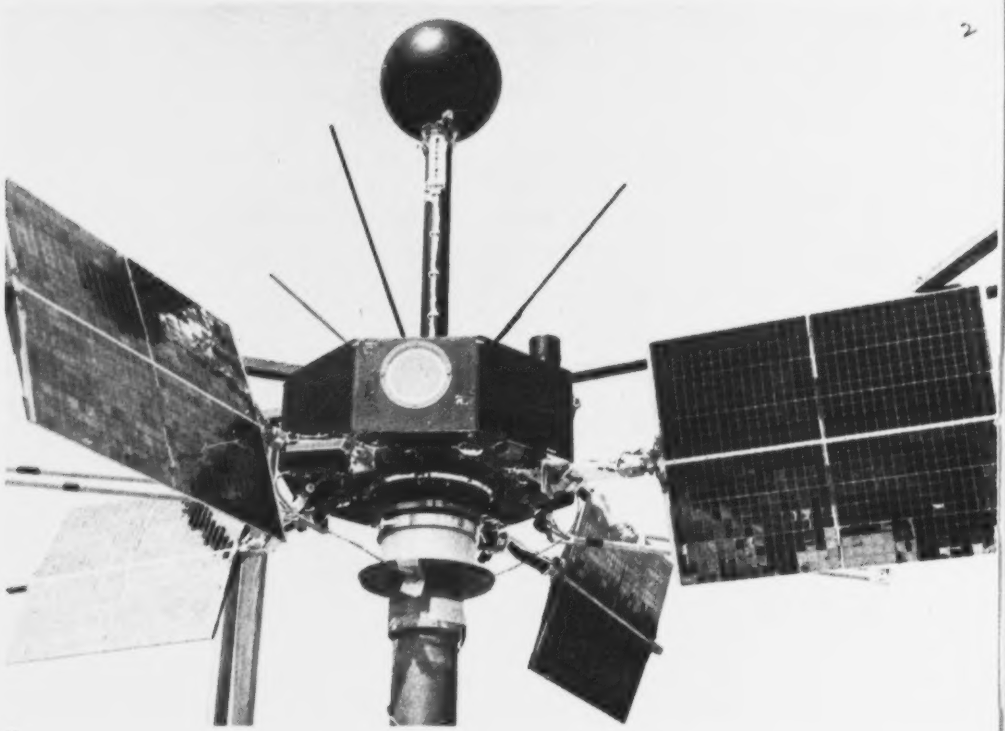
not be trapped and would ordinarily escape the Earth completely. A neutron, however, is not a fundamental particle; that is, it splits spontaneously into simpler particles—a proton, electron, and neutrino. If a neutron splits (decays) while in the region of the Van Allen belts, the resulting proton and electron may be captured by the belts. This is called the neutron albedo hypothesis.

The outer belt is more mysterious. First of all, though, the distinction between the two belts is somewhat blurred. Electrons and protons are trapped in both regions; there is also a slot between them where radiation levels are lower. Some scientists prefer to speak in terms of a single radition zone rather than two well-defined belts.

Consider protons alone. Van Allen's early map indeed showed a zone of high radiation levels beyond the inner proton belt; but was it composed of protons? The National Aeronautics and Space Administration (NASA) began a comprehensive program aimed at answering such questions when it was founded in 1958. Using scintillator counters aboard Explorer XII in 1962, Leo R. Davis and James M. Williamson, at Goddard Space Flight Center, showed that there are more protons in the outer belt than the inner belt. However, proton energies in the outer belt are too low to contribute to the particle counts observed by Van Allen. Again, a rocket provided the necessary clues. In 1959, a rocket carried an electron spectrometer (an instrument that sorts out electrons according to their energies) into the outer belt region. J. B. Cladis and his associates at Lockheed concluded that the spectrometer data proved that the penetrating component of outer belt radiation was composed of high energy electrons.

Another facet of the problem was discovered in the early 1960s by Brian O'Brien, then at the University of Iowa. Using data from the Injun I and Injun III satellites, O'Brien demonstrated that auroral activity was linked to sudden increases in the population of outer belt electrons. No one is certain where these electrons come from, but some of them may splash over from the outer belt into the auroral zones, causing our northern lights.

Recent satellites have continued the exploration of the Earth's great radiation belt and mapped it in greater detail. The more the belts are studied the more complex they seem. First, they are strongly affected by the Earth's magnetic field, which has long been known for its vicissitudes; second,



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both the belts and the Earth's magnetic field depend upon the whim of the Sun, which can reach across 93,000,000 miles to jostle and distort both. The rest of the radiation belt tale, therefore, must be told in terms of our planet's magnetic field and the long reach of the Sun.

The Magnetic Shell Around The Earth

The Earth's first line of defense against solar and cosmic projectiles (that is, charged subatomic particles) is its magnetic field. Magnetic lines of force can deflect charged particles as well as trap them. Our magnetic field thus constitutes one of the three barriers that insulate us from the turmoil of outer space. The magnetic field's protection is so effective that Earth-bound science remained quite innocent of—even naive about—the true character of the Earth's field until satellites began to explore it.

A pre-satellite picture of the Earth's magnetic field was drawn as early as 1600 by William Gilbert in his famous work *De Magnete*. Detailed maps produced for navigators provided mathematicians such as Laplace, Poisson, and Gauss with enough data to create a mathematical model. In essence, the model assumed a (fictitious) bar magnet inside the Earth.* To account for the fact that the magnetic poles are not geographically opposite one another, mathematicians had to bury their magnet some 450 miles from the center of the Earth. The mathematical model predicted that the Earth's lines of force would gently curve around from pole to pole, creating the kidney-like pattern so familiar from magnetic experiments with iron filings in school.

As always, however, a few perceptive individuals swam against the current of scientific thought and stated that the Earth's field out in space might not resemble that of a bar magnet at all. Von Humboldt, the great German naturalist, was the first to suggest that all was not serene in space. In 1806, he found that the peculiar quiverings of his compass needles, a phenomenon known for centuries, could be linked to auroral displays. Soon, scientists discovered that *both* the auroras and von Humboldt's magnetic storms were stimulated by solar activity. With this long range Sun-Earth intimacy in mind, Sidney Chapman and V. C. A. Ferraro postulated in 1931 that the Sun might emit bursts of plasma† during solar storms, and that these plasma clouds might completely envelop the Earth and bottle up its magnetic lines of force.

** Many geophysicists believe that the Earth's field is created by the dynamo action of an electrically conducting fluid circulating inside the Earth.*

† A plasma is a mixture of positive ions, negative ions and neutral atoms that is electrically neutral. A plasma can conduct electricity.

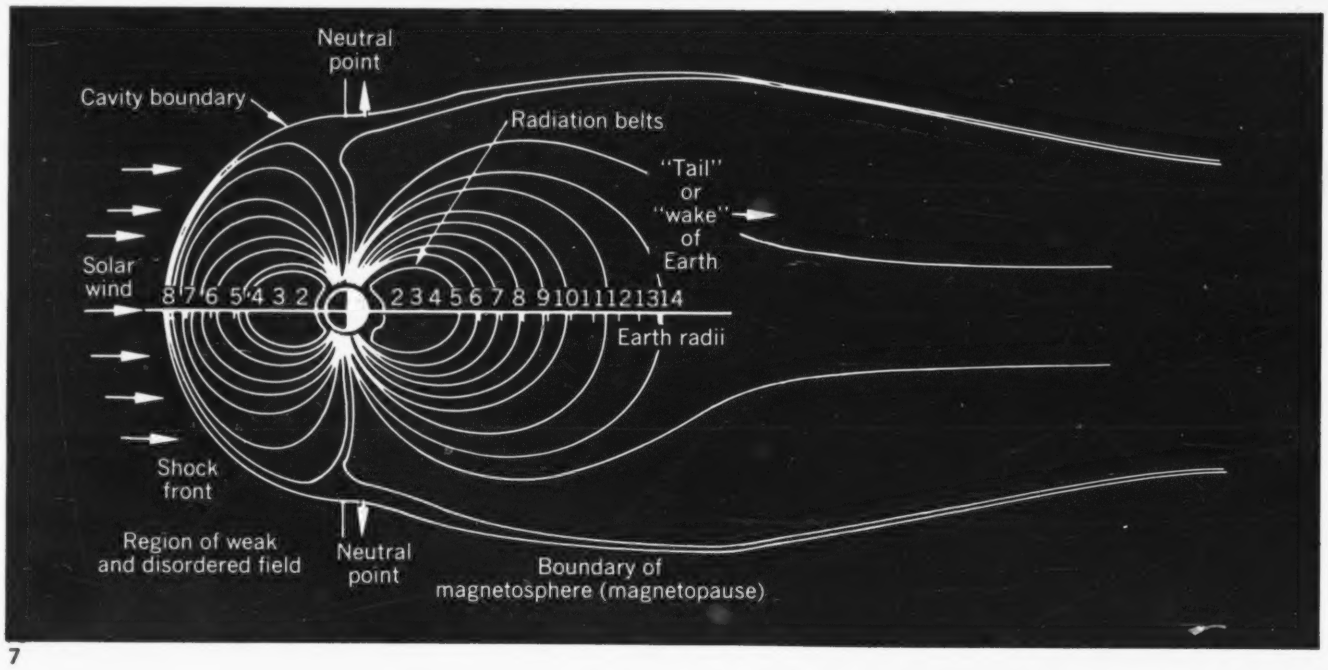
6 *Explorer XVIII, the first IMP (Interplanetary Monitoring Platform), was launched into a highly eccentric orbit on Nov. 26, 1963, repeatedly piercing the magnetopause. Its data helped draw a more accurate map of the magnetosphere.*

NASA's Vanguard III was the first U. S. satellite to carry a magnetometer into space, but its orbit did not take it beyond the Van Allen belts. In 1958 and 1959, the Pioneer III space probe and the Explorer VI satellite penetrated deep into space. Both found that the Earth's field was in a state of extreme disorder five to eight Earth radii out. At this time, discovery of the Van Allen belts had already revolutionized thinking about what was happening a few hundred miles overhead. It now appeared that there might be a steady wind of solar plasma buffeting the Earth. As this electrically conducting wind blew against the Earth's magnetic lines of force it drove them backwards, away from the Sun. On the night side it drove them far downstream from the Earth. In terms of 1959 thinking, the Earth was enclosed in a streamlined, tear-shaped bottle, with magnetic walls that kept most of the solar wind outside. Over the surface of this protecting bottle, and as a result of the full force of the solar wind, shock fronts formed similar to those in front of a supersonic plane. When Explorer VI and Pioneer III passed through these shock fronts they recorded the turbulent situation on their magnetometers.

Many of the Explorer satellites launched in the early 1960s included magnetometers and solar plasma detectors in their payloads. This permitted scientists to draw a better picture of the magnetic bottle that the Earth carried with it around the Sun. In particular, Norman Ness, at Goddard Space Flight Center, helped refine the picture with his magnetometers on the IMP (Interplanetary Monitoring Platform) satellites. Ness confirmed the existence of a shock front about ten Earth radii out in the direction of the Sun. Within this shock front was the bottled magnetic field of the Earth; outside was the weaker interplanetary magnetic field created by the Sun. As the IMP satellites probed the leeward side of the Earth, away from the Sun, magnetometer readings showed the trailing tip of the teardrop to be hundreds of thousands of miles long. It was more like a long "tail." Even the Moon passed through it on occasion.

Today's pictures of the Earth's field bear little resemblance to those idealized dipole fields drawn in the 1950s. The Earth is now pictured as existing in a very elongated magnetic bottle oriented with

7 *A recent view of the magnetosphere shows the Earth with a long tail extending hundreds of thousands of miles leeward of the Sun.*



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its long direction pointing away from the Sun. The shell of this bottle is called the magnetopause, and the space inside is the magnetosphere, although it is far from spherical in shape.

The details of the Sun-molded magnetosphere are still being investigated. The dimensions and character of the Earth's tail have not been fully determined. Perhaps charged particles find that this tail, wherein magnetic fields are very low, is a chink in the Earth's magnetic armor. The Van Allen belts may be populated by invaders entering through this route. Further, the propagation of magnetic storms, with their magnetohydrodynamic waves, is not well understood. We have come a long way from von Humboldt's nervous compass needles, but more discoveries are imminent.

Wind From The Sun

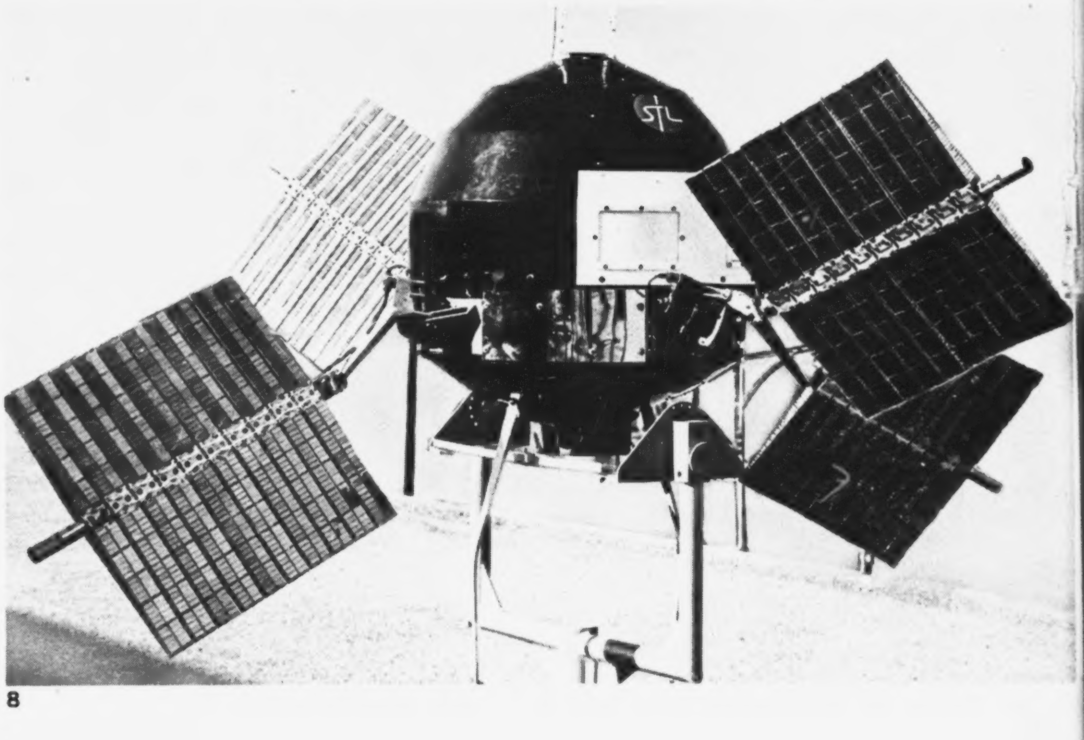
In the turbulent drama high above our atmosphere, the Sun is the obvious villain, continuously stirring the particle populations of the Van Allen belts and pummeling the magnetosphere with bursts of plasma. This transient and intransigent behavior is superimposed upon the steady-state solar wind.

The idea that the Sun could spew forth ionized but electrically neutral gas seems to have originated with Felix Lindemann, an English physicist, in 1919. Chapman and Ferraro had employed this concept in 1931 as a possible explanation of magnetic storms. This was all untested theory, though, and the transient magnetic storms required that the Sun emit vast globs of plasma in the direction of the Earth only occasionally.

The German physicist, L. F. Biermann, tried to explain comet tails in the early 1950s by suggesting that there might also be a constant solar wind blowing through the solar system. Biermann proved that comet tails, which always point away from the Sun—regardless of the comet's direction of travel—could not be explained by the pressure of sunlight or any then known mechanical force. He suggested that the Sun boiled off a continuous flux of plasma that blows comets' tails as wind blows a candle's flame.

Just prior to the first satellites, the American astrophysicist, Eugene N. Parker, showed theoretically that the Sun should be boiling off vast amounts of plasma as a consequence of its high temperature. This outrushing plasma would fill the whole solar system, bathing all comets and planets.

Thus, as the U.S. and Russia prepared to launch their first satellites in 1957, there was a substantial



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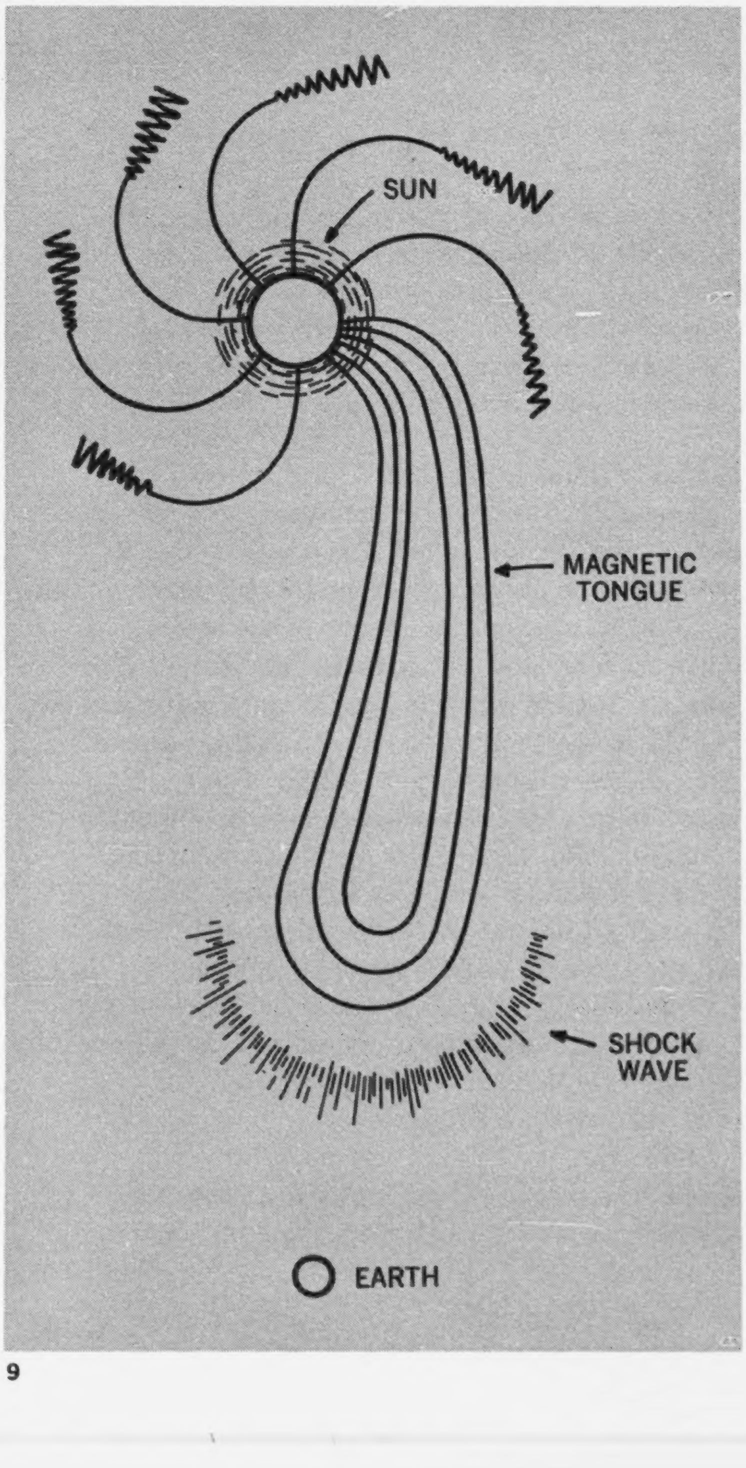
8 *Pioneer V, shown mounted on the top of the Thor-Able rocket just prior to launch. The Pioneers gave us our first good solar wind data outside the magnetopause.*

body of theory predicting the existence of a solar wind, as Parker so aptly named it, traveling at several hundred miles per second and consisting of less than 100 particles per cubic centimeter. In retrospect, the bottling up of the Earth's magnetic field by the magnetopause should not really have startled anyone, but it did.

Strangely, in view of the good chances of finding a solar wind, the early satellites did not carry plasma probes—the instruments which collect and measure low velocity ions and electrons. Not until the Russian Moon probe Luna 1 was launched on January 2, 1959 did anyone try to measure the solar wind directly. The first U. S. plasma probe was on Explorer X, launched March 25, 1961.

9 *Idealized view of a plasma tongue erupting from a solar flare. These plasma storms are not as well organized as the sketch shows.*

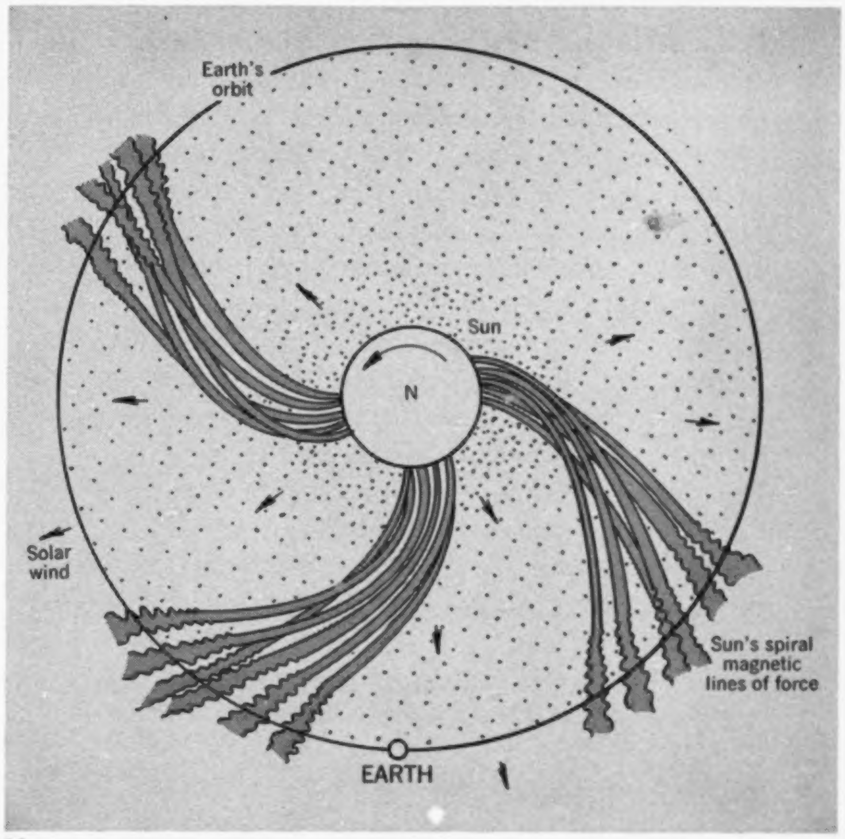


Both spacecraft confirmed the fact that a steady solar wind blows past the Earth at about 200 miles per second (300 km/sec). More detailed study of the solar wind had to wait until NASA launched its first planetary probe, Mariner II, which departed for Venus on August 26, 1962. The plasma probe on Mariner II indicated that the average velocity of the interplanetary solar wind along the spacecraft's trajectory was actually about 300 miles per second (500 km/sec). The particles—mostly protons and electrons with about 5% helium ions—number about 5 per cubic centimeter.

Scientists say steady-state solar wind to differentiate between the wind that blows all the time and the great plasma tongues that erupt sporadically from the Sun's surface during solar flares. The steady-state solar wind is really quite gusty, as plasma probes on the Mariner and Pioneer probes have demonstrated. Terrestrial optical and radio telescopes show the Sun's surface and corona to be in continual turmoil, so it is not surprising to find the solar wind (really a long-range extension of the corona) to be correspondingly fitful.

We see a visible flare lash out from the Sun's surface; a day or so later, the shock wave preceding the plasma increase slams into the Earth's magnetosphere, causing the first phase of a magnetic storm; soon the Earth is engulfed by the plasma increase. During the main phase of the magnetic storm, long distance terrestrial communications are disturbed, and there is a noticeable drop in the intensity of cosmic rays arriving at the Earth's surface.*

** Called a Forbush decrease, the drop is due to the fact that the plasma tongue has added a second magnetic bottle around that created by the magnetosphere. Fewer cosmic rays penetrate both walls.*



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10 *The steady solar wind drags the Sun's magnetic lines of force with it in a radial direction. Sun's rotation causes spiral effect.*

The Sun has a magnetic field that may pervade the entire solar system, from Mercury to beyond Pluto. This field would be like that of a bar magnet if it were not for the heavy handed solar wind. The solar wind blows so hard that magnetic lines of force are blown out radially as if they were paper streamers in a gale. The Sun's magnetic lines of force would stick straight out radially were it not for the Sun's rotation every 27 days. Rotation causes a garden-sprinkler effect, resulting in spiral lines of force. Further, the turbulence in the solar wind tosses the lines of force about, giving the diagram of them a frizzled look.

At the Fringes of Our Atmosphere

Far beneath the stormy magnetopause and radiation belts, a thin film of air clings to the Earth. In thickness, our atmosphere might be compared to the skin of an orange, for it is only a few hundred miles thick compared with the Earth's diameter of some 8000 miles. In terms of substance, though, the orange analogy fails. The atmosphere weighs only 14.7 pounds per square inch—equivalent to 34 feet of water. Yet, this thin gas we call air gives us oxygen to burn with the food we eat; aircraft wings get lift from it; and, most important, it shields us from the dangerous solar ultraviolet rays and much of the radiation not deflected or trapped by our magnetic field.

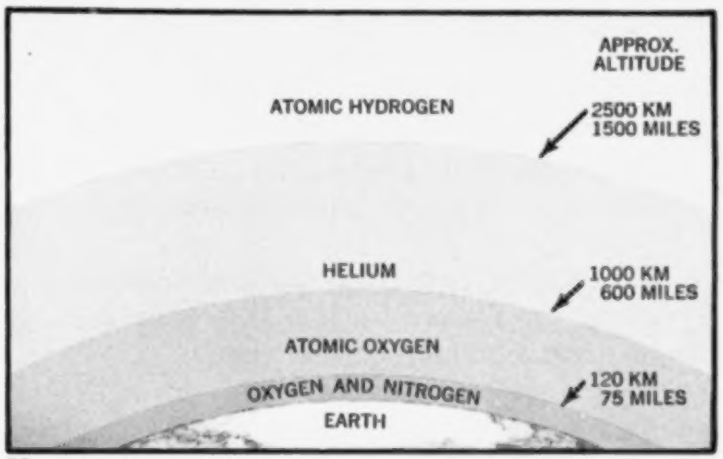
The lower atmosphere, with its immense cyclones and anti-cyclones swirling across the globe, can be studied by watching meteorological balloons, by sending up instruments on balloons and rockets and listening to the signals they send back, and, of course, by picture-taking satellites.

Focus on that part of the atmosphere above 50 miles. It is often called the thermosphere or exosphere to distinguish it from the layers below.

It is a thin mixture of gas atoms and molecules—gas so thin at 200 miles altitude that a gas molecule travels a mile, on the average, before it hits another. Being so diffuse, this air does not behave like the relatively thick and viscous stuff we know at sea level.

Satellite instrument designers have found that air temperature cannot be measured with an ordinary thermometer; the air is too thin and contains too little heat to be able to affect the thermometer. Instead, they have to measure the speeds of the atoms, molecules, ions, and electrons that make up the air. From speed they compute kinetic temperatures of over 1000°K in the thermosphere. This hot, rarefied world changes from day to night, from season to season, from sunspot peak to minimum. It glows as the Sun excites its atoms. Around the poles it flickers with ghostly auroras. It is such a different world that dozens of satellites have been sent up to participate in exploring it. More specifically, NASA has constructed a series of Atmosphere Explorers, Ionosphere Explorers, and Orbiting Geophysical Observatories to probe this mysterious region.

All satellites that brush the top of the atmosphere with their orbits help scientists infer the density



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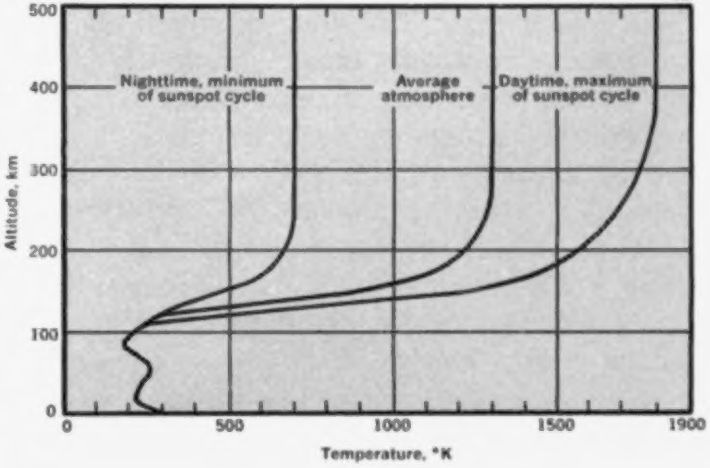


11 *The heavy atoms and molecules settle predominantly toward the bottom of the atmosphere.*

12 *The temperature of the thin atmosphere at satellite altitudes is very high. It is affected strongly by the rotation of the Earth and the sunspot cycle.*

of the atmosphere. The early satellites surprised everyone by slowing down and reentering the atmosphere rather rapidly. The upper atmosphere was denser than expected. Precise telescope and camera tracking of satellites, especially the Echo balloon satellites, soon revealed that the upper atmosphere was not only higher and more dense, but more fickle than supposed. Sunlight, especially, had a great effect. The part of the atmosphere facing the Sun bulges out conspicuously. As the Earth rotates, the bulge travels around the Earth once a day like a monstrous tidal wave. At 400 miles altitude, the kinetic temperature of the Sun-heated bulge may be almost 800°K higher than the atmosphere on the dark side of the Earth. Further, densities and temperatures change markedly during the eleven-year cycle of solar activity. So, just by watching satellites in their orbits and using the methods of thermodynamics, scientists with tracking equipment all over the world were able to draw a radically new picture of the upper atmosphere.

By studying the orbital data for Echo I, the Belgian aeronomist Marcel Nicolet was able to deduce in 1961 that a layer of helium exists in the region from 600 to 1500 miles altitude when the Sun is active. This was confirmed in 1963 by a mass spectrometer installed on Explorer XVII, which detected the helium directly. From the standpoint of gross composition, the atmosphere is four-layered. The major constituents are: the familiar oxygen and nitrogen mix at the lowest level; then, atomic oxygen; next, the newly discovered helium-rich layer; and finally, the lightest gas of all, atomic hydrogen. Our atmosphere is stratified with the heaviest atoms and molecules at the bottom and the lightest at the top.

It is startling to discover that the Earth has a corona rather similar to that of the Sun. Satellites find no sharp upper boundary to the atmosphere. A hydrogen geocorona reaches outward thousands of miles, eventually merging imperceptibly with the interplanetary milieu—really the extended solar corona. Hydrogen atoms in the geocorona, heated by the Sun, attain such high velocities that they can escape the gravitational pull of the Earth altogether. Like the Sun, the Earth is continually releasing hydrogen, a little helium, and a few heavier elements.

Sounding rockets and ground observations of chemicals released at high altitudes have detected tidal oscillations in the atmosphere similar to those observed in the oceans. More fascinating, however, are the so-called gravity waves, which move upward from some unknown disturbance in the lower atmosphere and surge through the upper layers of the atmosphere. The horizontal width of the wave motion may be several hundred miles in extent, with periods on the order of 100 minutes.

As if the atmosphere were not complex enough with its stirrings and pulsations, it also turns

13

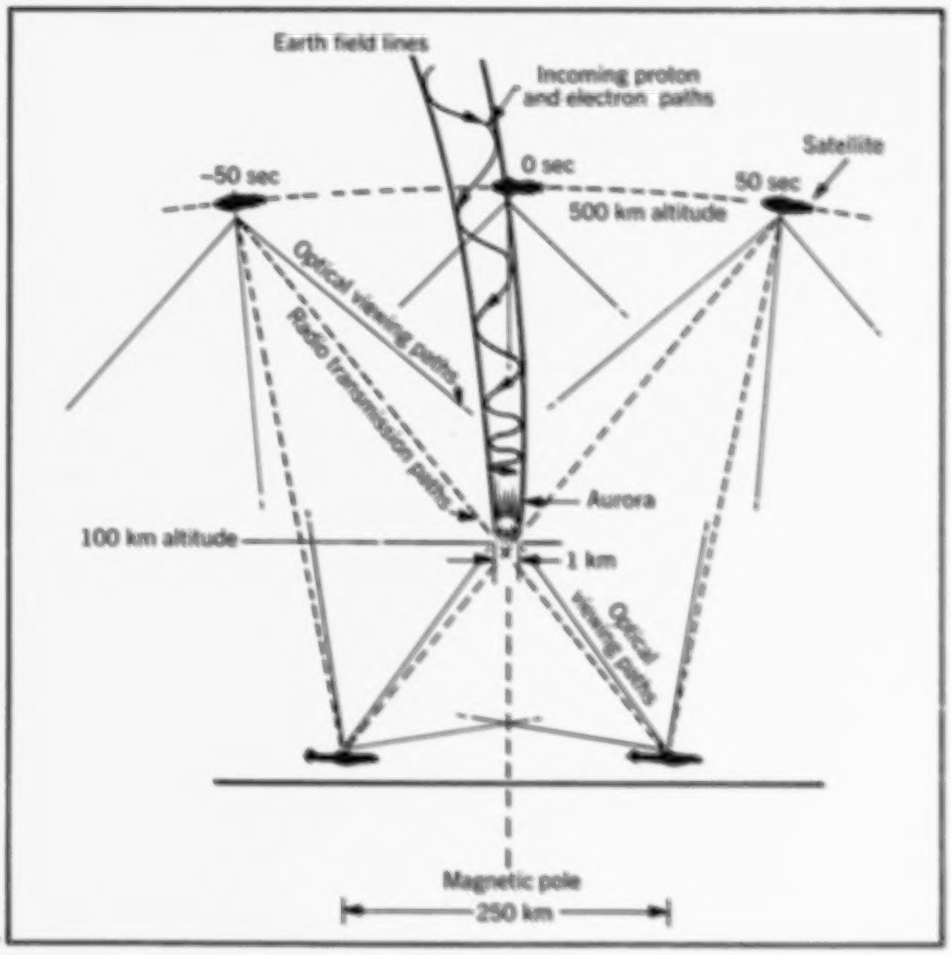
13 *Satellites like this Direct Measurements Explorer (Explorer XXXI) have been able to provide data taken directly in the ionosphere and upper atmosphere.*

out to be the scene of exotic chemical reactions. The best-known reaction occurs when ultraviolet light from the Sun dissociates diatomic oxygen molecules. Single oxygen atoms then combine, on occasion, with diatomic oxygen molecules to form triatomic ozone.

On a clear Moonless night away from city lights, a faint glow in the sky can be seen that increases toward the horizon. This is the airglow, a complex phenomenon that no one has unraveled satisfactorily. Airglow—similar in some ways to the weird greenish light emitted by the polar auroras—is emitted by excited atomic oxygen, the hydroxyl ion (OH^-), nitrogen, and other atoms and free radicals. In some undetermined way, solar energy stimulates unusual chemical reactions in the rarefied upper atmosphere that we have difficulty in reproducing in terrestrial laboratories. Sounding rockets and satellites equipped with spectrometers analyze the airglow and help scientists identify the chemical reactions transpiring a few hundred miles up. Despite numerous satellite and rocket experiments, airglow mechanisms remain elusive.

More spectacular are the colorful polar auroras. The dancing auroral flames and draperies are

14 *Aircraft and satellites can make simultaneous observations of auroras from different vantage points.*


Earth field lines
Incoming proton and electron paths
Satellite
−50 sec
0 sec
50 sec
500 km altitude
Optical viewing paths
Radio transmission paths
Aurora
100 km altitude
1 km
Optical viewing paths
Magnetic pole
250 km

14

usually green and blue-green, with occasional patches and embroidery of pink and red. Somehow, high in the atmosphere, the Sun, the Earth's magnetic field, and the oxygen and nitrogen atoms in the atmosphere work in concert to put on this eerie display. Many satellites in the NASA Explorer series, the Observatory series, and Air Force programs have transported plasma probes, spectroscopes, and other instruments into the auroral zones to try to divine the origin of the auroras. Satellite experiments have been coordinated with rocket and aircraft flights to obtain top and bottom views of the auroras. Even with all this effort, the auroras remain enigmatic.

For a while scientists believed that the auroras were stimulated by spillover of charged particles from the radiation belts which are magnetically focused on the polar regions. The logic seemed sound: the disturbed Sun dispatches globs of plasma in the direction of the Earth; these are caught and focused by the Earth's magnetic field; the solar particles precipitate into the auroral zones; there they excite atmospheric atoms and create the auroras. But calculations show that the energy emitted by an auroral display is considerably greater than that present in the motion of charged particles in the radiation belts. In fact, it may be that the radiation belts are actually populated when the Earth's magnetic field captures electrons from the auroral regions instead of vice versa. Obviously, more auroral experimentation is needed.

The ionosphere is better understood than the auroras. The ionosphere is created when solar ultraviolet radiation and X-rays ionize atoms in the upper atmosphere. The freed electrons are highly mobile and cause electromagnetic effects as well as the reflection of radio waves. The existence of an ionosphere was suggested by Gauss in 1839 and in 1878 by the Scottish physicist Balfour Stewart. Stewart postulated that minor variations in the Earth's magnetic field were caused by fluctuations of electrical currents at high altitudes. His idea lay dormant until Marconi proved in 1901 that wireless signals could be transmitted across the Atlantic. Beginning in the 1920s with the experiments of Edward V. Appleton and M. A. F. Barnett, in England, and Gregory Breit and Merle A. Tuve, in the United States, science began to probe the bottom of the ionosphere with pulsed beams of radio waves. By measuring the times of the echos, the heights of the reflecting layers were determined. The ionosphere, however, turned out to be complex and ever-changing. By increasing the frequency of the radio waves, one can probe farther into the ionosphere. The critical reflection frequency depends upon the density of free electrons. Radio waves above 20 MHz (megahertz)* pass right through the ionosphere into outer space. Work at various frequencies soon disclosed that the ionosphere is layered, and that the layers shift up and down during the day; layers sometimes fade away completely and then reappear. When NASA was created in 1958, it was already obvious that one of its missions would be to explore this ionized region of the atmosphere further.

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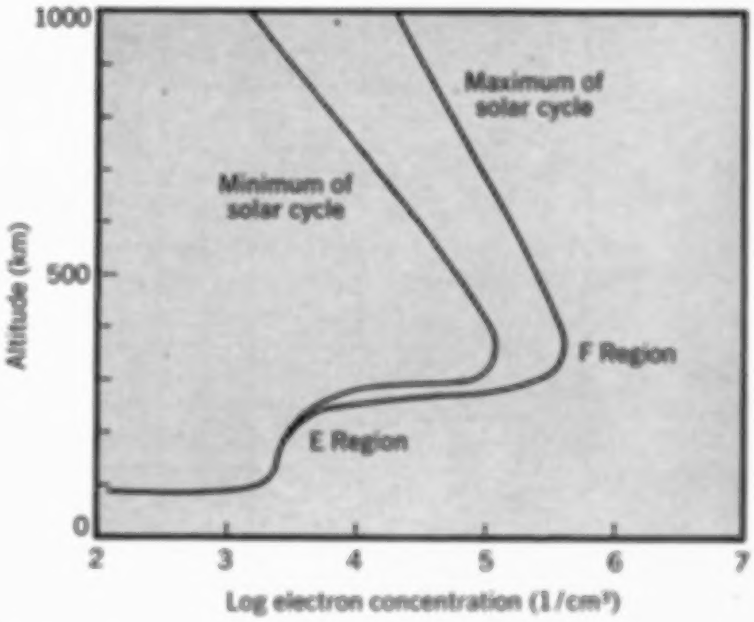

15 *The layers of the ionosphere are created by solar radiation. Like the temperature of the upper atmosphere, electron concentration varies strongly with solar activity.*

Sounding rockets had been making brief incursions into the ionosphere for many years, and the National Aeronautics and Space Administration naturally continued with this technique. But how could satellites be used to advantage? Satellites could not orbit in the relatively dense D region of the

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** One megahertz = one megacycle per second (old terminology) = one million cycles per second.*

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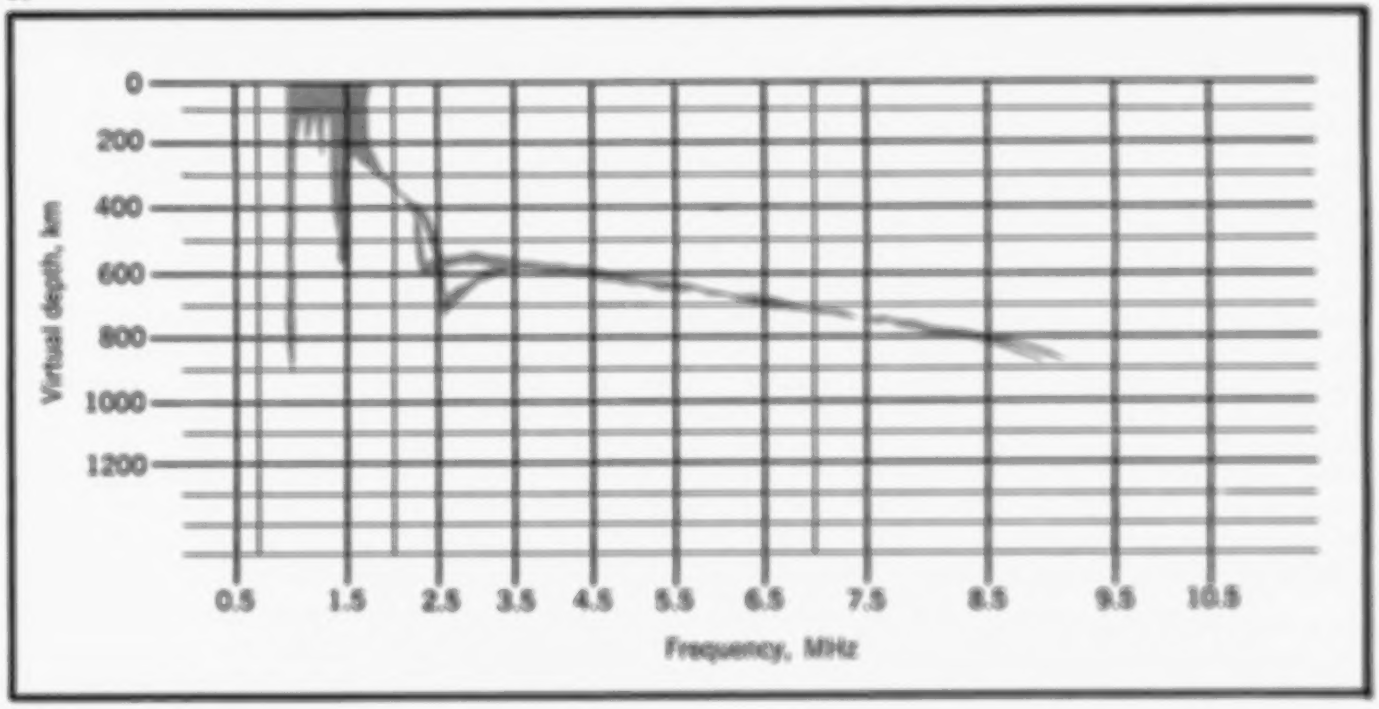

ionosphere, which in the daytime extends roughly from 35 to 55 miles. Satellites would have to look down on most of the ionosphere.
In this position, they could direct pulses of radio waves from above rather than below. This approach was first used on Alouette I, a joint U.S.-Canadian satellite, launched on September 28, 1962.
Alouettes I and II and Explorer XX are all termed topside sounders, although they also contain other experiments. Collectively, they have been able to map the upper portion of the F region, which could not be sounded from the ground. These maps of electron density have to be drawn for the entire Earth, for various times during the day, season, and sunspot cycle.
Like the neutral atmosphere, the solar plasma, and the radiation belts described earlier, the structure of the ionosphere is complex and highly variable in time. The layers are wrinkled, shifting, and wax and wane as the solar input changes and as the whole atmosphere stirs in response to thermal and electromagnetic forces.

Satellites can also make direct *in situ* measurements of the so-called diffusion-dominated region of the ionosphere, roughly above 150 miles altitude. Direct measurement satellites, such as Explorers VIII and XXXI, have measured electron and ion densities with various electrical probes.

Beacon satellites—Explorers XXII and XXVII—have sent out radio signals to receivers on the Earth below to investigate the different ways in which radio waves can be propagated through the ionosphere. Ionosphere ducting is of great interest, because signals sometimes can be transmitted around the world if they are trapped between dense layers of electrons. A simple way to study the ionosphere is simply to listen—with a radio, of course. Receivers on the ground and on satellites can hear whistlers, which are radio signals created by lightning flashes. Whistlers propagate through the ionosphere, creating much of the background noise we hear on ordinary radio sets.

Summarizing briefly, the upper atmosphere consists of several co-existing populations of particles—ions, electrons, free radicals, neutral atoms and molecules—that interact not only with each other, but with the radiation belts above and the dense neutral atmosphere below. The whole brew is heated and stirred by the Sun and changes with every electromagnetic disturbance that happens by.

The Sun: Interplanetary Weather Maker

The solar wind blows through the solar system causing comet tails to flare out, stimulating the Moon to luminesce, to say nothing of roiling the Earth's tenuous upper atmosphere. Solar radiation—both

16 Ionograms, such as this one taken by Alouette I, permit scientists to chart electron density from the top of the ionosphere. The depth at each frequency is found by timing the echoes.

17 Intensity of solar radiation above the Earth's atmosphere. Actually more than half the energy in sunlight never reaches the surface. Radio portion of the spectrum not shown.

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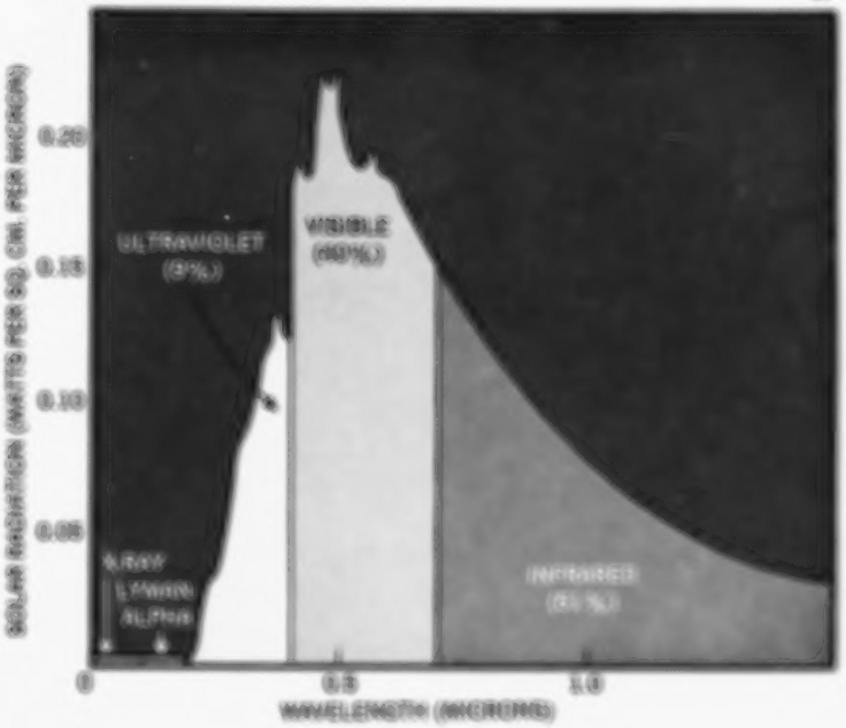


electromagnetic and particulate in nature—also affects the Earth. Radiations from the Sun permit us to diagnose our nearest star and find out what makes it work. If we can understand the Sun, we will also know how many other stars in the universe work; we will also know better how the Sun controls interplanetary weather.

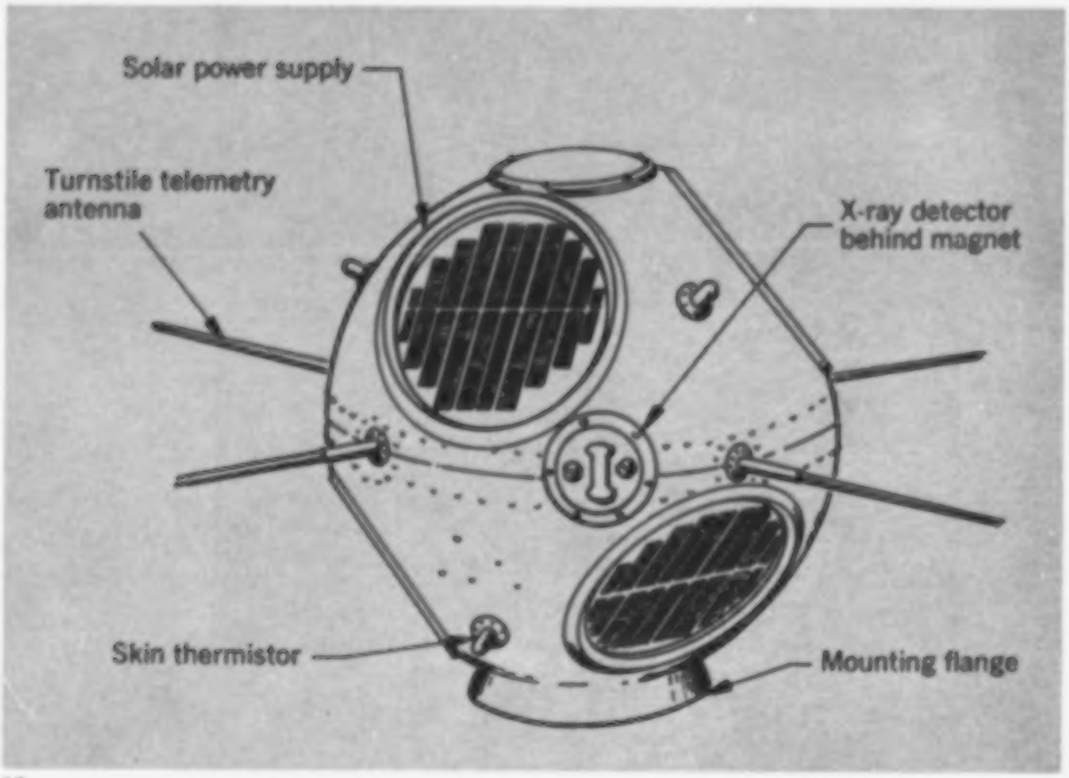
We can see the Sun so well from Earth, why bother with rockets and satellites? The answer, of course, is that we see only those parts of the sunlight and radiation flux that penetrate all the way through the atmosphere and even then atmospheric turbulence hampers observations. To see solar X-rays, high energy protons, and the far ultraviolet, instruments must be carried above the atmosphere and pointed accurately at the Sun.

Long before the advent of satellites, scientists were mounting spectrographs on high altitude balloons and rockets. Captured V-2 rockets, for example, took spectrographs up over 100 miles where they automatically found the Sun, locked onto it, and made spectrograms. The U.S. Naval Research Laboratory (NRL) pioneered many such rocket techniques in the 1950s. Even though the rockets broke through the atmosphere for only a few minutes, NRL scientists were able to measure the Sun's radiation in the far ultraviolet region for the first time.

When long-lived satellite instrument platforms became available in 1958, NRL, the Air Force, and NASA began planning new solar instrumentation. NRL was first into space with such instruments when it launched a small piggyback satellite called Grab 1 (later renamed Solrad 1), on June 22, 1960. Piggyback means that Grab 1 hitch-hiked a ride into orbit on a larger satellite—Transit 2A, in this instance. Grab 1 carried small ionization chambers that monitored solar X-rays and the Lyman-alpha line of hydrogen, which helps diagnose solar processes but is too far in the ultraviolet to see from the Earth's surface. With Grab 1, its several successors, and sounding rockets, NRL was able to correlate visible solar events with solar X-ray and Lyman-alpha activity.

18 *The piggyback satellite, Greb 1 (Solrad 1), was launched on June 22, 1960. The Naval Research Laboratory installed X-ray and Lyman alpha detectors to monitor the Sun's radiation.*

19 *OSO II prior to launch. The pointable sail is mounted on a nine-sided base approximately 44 inches across. Balls on arms contain pressurized gas to orient satellite in space.*



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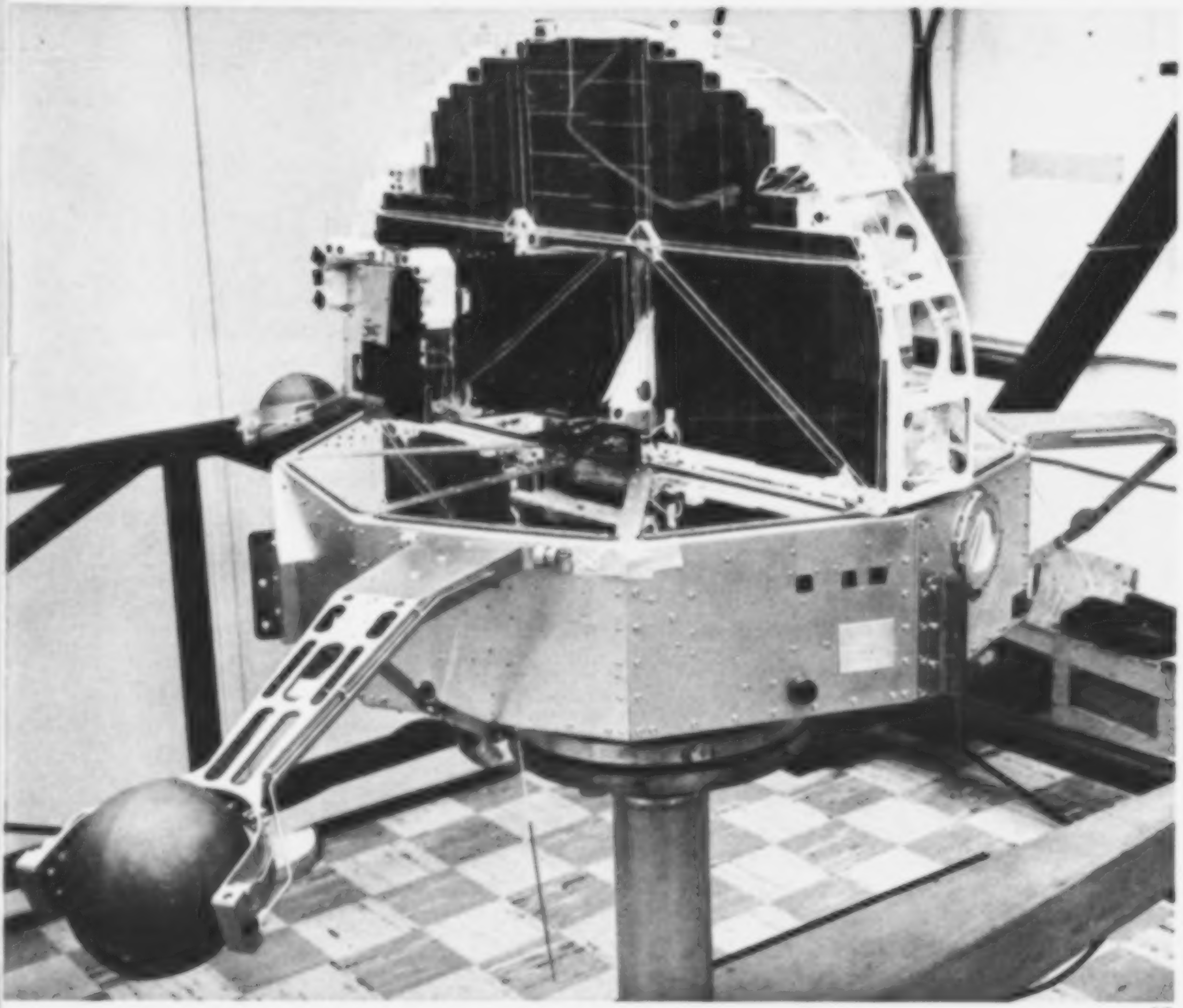
Although many NASA satellites have carried various instruments for studying the Sun, the series of Orbiting Solar Observatories (OSOs) have been the most productive. The great utility of the OSOs derives from the fact that one section of the satellite (the sail) continuously points at the Sun while another part (the wheel) spins, stabilizing the satellite and permitting other instruments to scan a large sector of space. Furthermore, the pointed sail section includes a scanning platform that gives instruments the opportunity to map the Sun's face by sweeping zig-zag fashion across it.

The first of several OSOs was launched on March 7, 1962. They carry a tremendous variety of optical instrumentation—mostly designed to detect X-rays and the far ultraviolet portion of the spectrum. Spectrographs have been employed to examine the far ultraviolet spectrum. Going a step farther, spectroheliographs scan the Sun's surface, like a TV camera, giving us images of the Sun in different wavelengths. When a scientist wants to look only at the Sun's gaseous envelope, the corona, he flies a coronagraph, which blots out the Sun's bright central disk. In short, dozens of different satellite instruments have been monitoring and scanning the Sun since 1962.

What has all this instrumentation discovered? Most of the new knowledge of the sun involves: (1) Identification of highly ionized atoms of various elements on the Sun, (2) Better understanding of solar flares through analysis of X-rays and other short wavelength radiations they emit, and (3) Correlation of these radiations with geomagnetic disturbances and the eruption of plasma from the Sun's surface. In essence, we now understand our nearest star better. To illustrate, scientists are now confident they can forecast the development of a solar flare and thus give astronauts out in space plenty of time to take shelter before they are hit by bursts of solar radiation.



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Dust From The Sky

Roughly 1000 tons of meteoric dust sifts down through our atmosphere every day. Where it all comes from no one knows. In fact, one of the other big surprises in space physics has been the discovery that the Earth may swing around the Sun surrounded by a cloud of dust.

Meteorites* were ignored for a long time by organized science because it was manifestly impossible for stones to fall from the sky. Only after the little French town of L'Aigle was bombarded by a volley of several thousands of such stones on April 26, 1803, did science finally come around and admit the existence of meteorites. The meteorites that fall to Earth, however, are millions of times larger than the particles in the Earth's halo of dust.

Spaceship designers, from the early dreamers like Jules Verne to engineers now building manned spacecraft, have worried about these interplanetary projectiles puncturing the walls of their vehicles. In the 1940s and 1950s, a number of engineers calculated the probability of a spaceship being perforated by a meteoroid. They based their estimates upon the numbers of meteor streaks seen high in the Earth's atmosphere and rockets that collected meteoric dust at high altitudes with flytrap devices. When they evaluated these data, engineers

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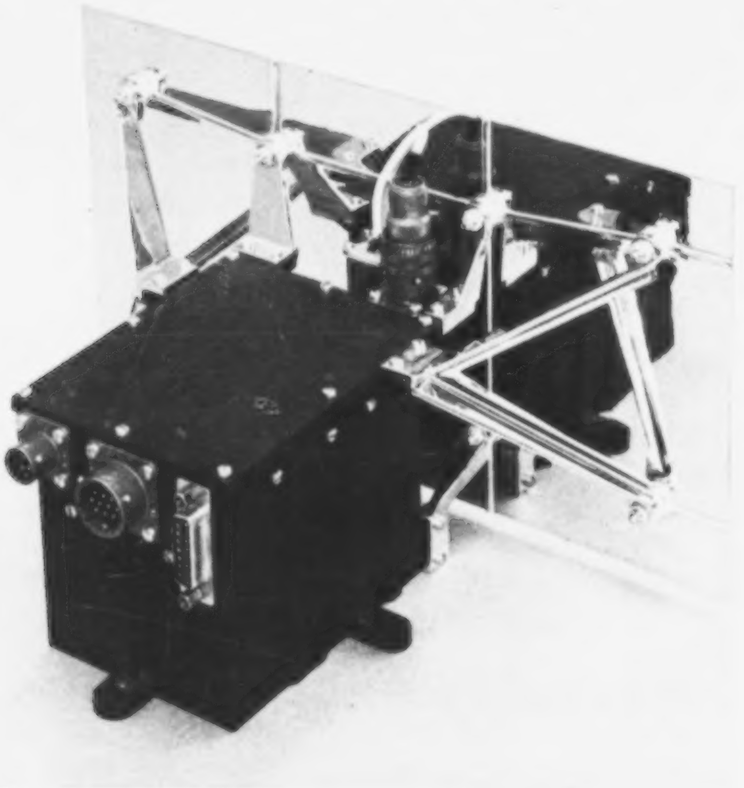
** In space a bit of meteoric material is called a meteoroid. If it is very small, it is a micrometeoroid. If it lands on the Earth, it is a meteorite. Meteors are shooting stars.*

20 *Acoustic sounding boards, such as this one built for Mariner II, have flown on many satellites.*



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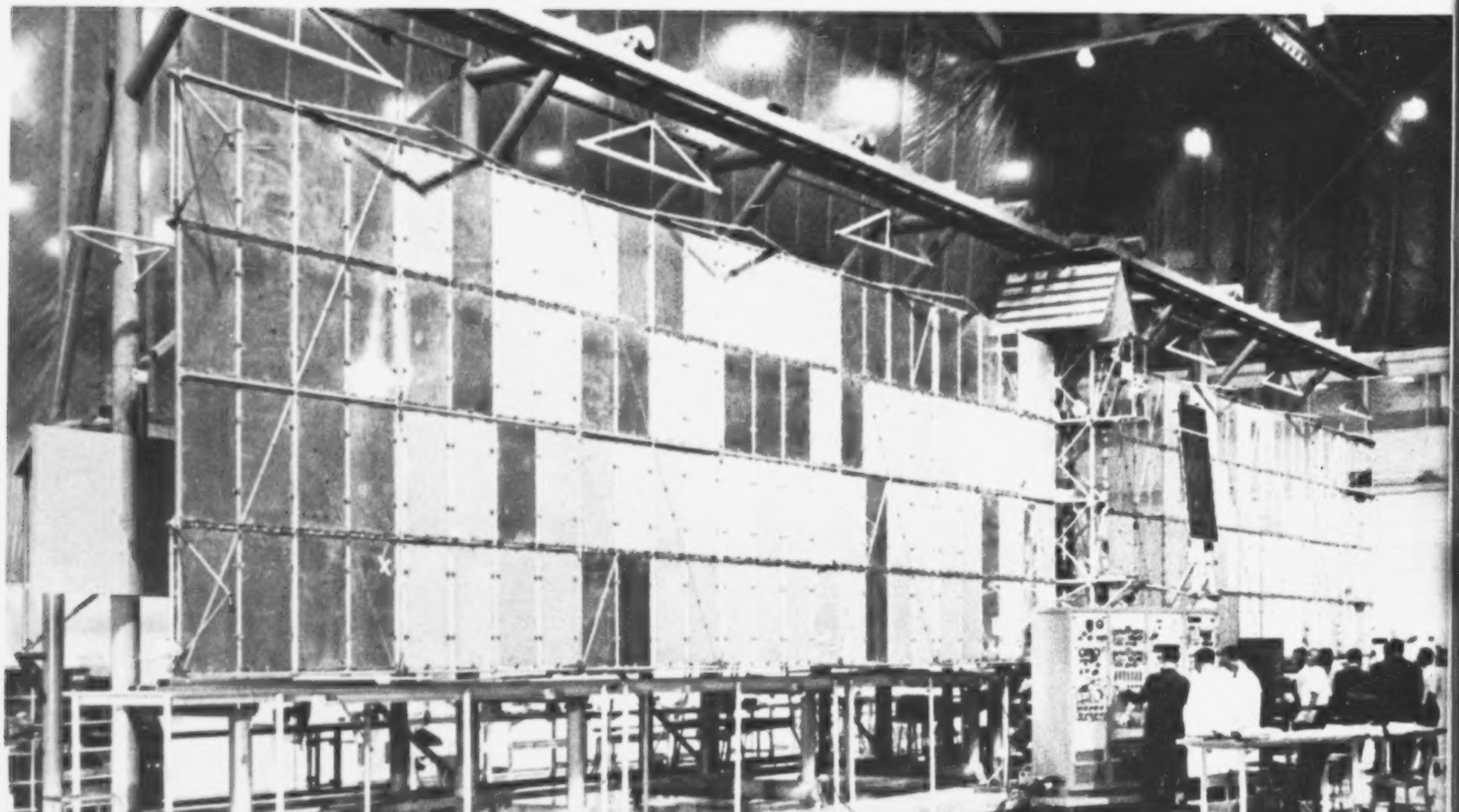
became concerned about the practicality of manned space flight. Consequently, many of the early satellites carried a wide array of instruments to record meteoroid impacts as well as their penetrating power.

A simple, straightforward way to check on the meteoroid hazard is to orbit thin-walled, pressurized bottles that send back signals when they lose pressure. Satellites such as Explorers XIII, XVI, and XXIII carried such pressurized cells. The first U.S. satellite, Explorer I, included two different micrometeoroid detectors; a closely wound wire card that would signal an open electrical circuit if hit by a meteoroid, and a piezoelectric microphone that listened for impacts. The latter instrument has been very popular on many satellites and deep space probes. Such sounding boards mounted on the Mariner probes to Venus and Mars reported a density of micro-meteoroids between the planets of some 10,000 times less than what they reported near the Earth.

21 *Huge "wing" of a Pegasus satellite, flown as a byproduct of Saturn I launch vehicle tests, to make micrometeoroid measurements. The wings were deployed in orbit to expose capacitor-type micrometeoroid detectors.*



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Although the existence of a dust cloud around the Earth has been inferred from experiment, the nature of the dust, the size of the particles, and the dust's origin remain unknown. One trouble is that we do not know whether this dust is fluffy or composed of hard sphericles, such as those we find so common in deep sea sediments. Until recently, we knew very little about so-called hypervelocity impact because we could not duplicate meteoroid speeds (up to 50 miles per second) here on the Earth.

Micrometeoroid data have accumulated from our many diverse instruments, from various orbits at different times of the year. The major conclusions reached over the past ten years of space research are: (1) The danger to astronauts in spacecraft or walking in space is very small, and (2) a dust cloud seems to hover around the Earth. In other words, there is a local population of tiny dust particles and a separate, less dense population of interplanetary meteoroids.

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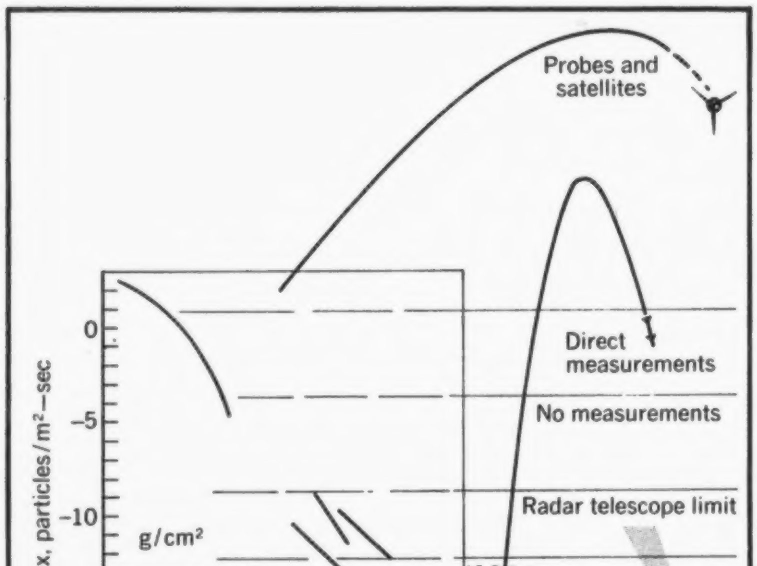


22 *Summary of micrometeoroid measurements made near Earth. Flux at left is cumulative in the sense that any point includes all meteoroids larger than the value on the abcissa. Dust cloud around Earth was discovered when deep space probes left Earth's gravitational field.*

Cosmic Rays

Around the turn of this century, early experimenters with radiation and radioactivity discovered that their instruments recorded some radiation no matter how much shielding they placed around them. At first, they thought it was due to natural radioactivity in the walls of their laboratories. After many vigorous and occasionally unscientific confrontations, the scientific world recognized the existence of a very penetrating form of radiation, which like meteorites could not come from outer space, but nevertheless did. Although we know a lot more about this cosmic radiation* today, we still do not know where it comes from and where charged particles get all their energy.

One of the key early cosmic ray experiments was carried out by the Austrian-American physicist, Victor F. Hess in 1911 when he carried radiation detection instruments to high altitudes in a balloon. His results were as surprising to the scientists of his time as the discovery of the Van Allen belts was to 1958 scientists. Hess found that cosmic ray intensity first decreased then increased, indicating an extraterrestrial rather than Earthly origin.

This discovery was contrary to expectations because this radiation was thought to originate in terrestrial materials. Since Hess' time, experimenters have been taking radiation instruments as high as they could get them—on mountains, in rockets and satellites—or as low as they could get them—in deep mine shafts.

** Cosmic radiation is not the same as the solar wind or the radiation in the Van Allen belts. It is far more penetrating than either.*

The high and deep approaches reveal some basic facts about cosmic rays. Cosmic ray researchers want to get high above our atmosphere on long-life satellites to escape the influence of the atmosphere. A few cosmic rays—the so-called primaries—zip right through the atmosphere into waiting instruments, but most of the incoming cosmic ray particles (mostly protons) smash into atoms in the air. The pieces of subatomic debris go on to cause more nuclear reactions, continuing until there is a shower of secondary cosmic rays. Scientists want to know what the unadulterated primary cosmic ray flux looks like.

In the 1920s and 1930s, it was fashionable to go down as well as up with cosmic ray instrumentation. The cosmic rays had great penetrating power, piercing a yard of lead almost as if it did not exist. Since many scientists thought that cosmic rays must come from well-defined sources in the heavens, they made their instruments directionally sensitive by using deep mine shafts for telescopes. As the Earth turned, the telescope would sweep out sectors of the sky; cosmic rays arriving from directions other than straight up would be mostly absorbed in the Earth walls of the telescope.

One of the major missions of NASA's sounding rockets, satellites, and balloons is to see if cosmic rays come from specific regions of the heavens. Hundreds of rocket flights and scores of satellites, such as the Energetic Particles Explorers and the Interplanetary Monitoring Platforms, have transported cosmic ray telescopes well out beyond the atmosphere. First, of course, electronic ingenuity had to replace Nature's unflyable telescopes with arrays of detectors connected in coincidence so that signals would be recorded only when a particle zipped through several detectors arranged in a straight line.

One well-known source of energetic particle radiation is the Sun. Until 1942, when the gigantic solar flare of February 28 caused cosmic ray counters all over the world to click a little faster, scientists thought that the Sun contributed little if any to the cosmic ray flux. Now, satellites and deep space probes (the Mariners and Pioneers) intercept these high energy solar particles soon after they have been spit out by solar flares. The results seem to show that these particles tend to follow the Sun's spiral magnetic lines of force—after the fashion of the much lower energy plasma tongues. In general, the solar cosmic ray particles have been found to be much less energetic, on the average, than the galactic cosmic rays arriving from outside the solar system.

In the search for the origin of cosmic rays, scientists at the Naval Research Laboratory have searched the sky for discrete cosmic X-ray sources using detectors on high altitude rockets. As the rockets rolled in their flight above the atmosphere, their instruments scanned the sky and detected at least 30 separate sources. If the particulate cosmic rays also originate from discrete sources, scientists will have to explain how these sources can accelerate particles to energies as high as 10^{20} electron volts.* Some cosmologists—Geoffrey Burbridge, for example—suggests that cosmic rays may be born in radio galaxies and the fantastically powerful quasars (quasistellar objects) that have been discovered recently.

Mapping the cosmic ray flux as a function of time has uncovered an unsuspected problem: as solar activity increases in its 11-year cycle, galactic cosmic ray intensity drops. The supposition is that the active Sun spews out more plasma and, in effect, builds a magnetic bottle around the whole solar system, deflecting cosmic rays and causing a Forbush decrease for the entire solar system. If this is true, we will not understand the true primary cosmic rays until we send interstellar probes well beyond the Sun's influence.

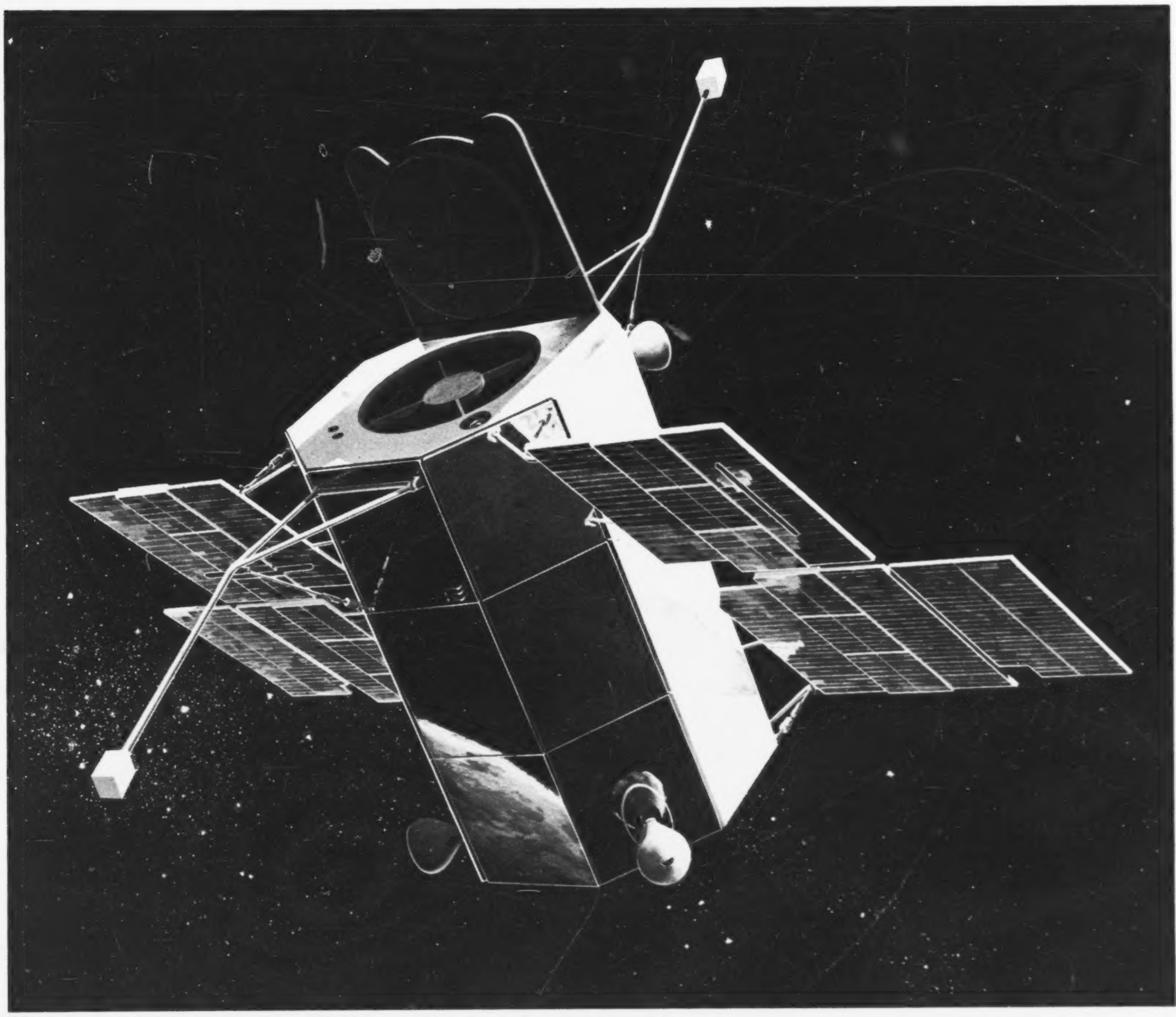
** Terrestrial atom smashers can achieve only about 10^{10} electron volts.*

23 *This artist's concept of the OAO (Orbiting Astronomical Observatory) illustrates the octagonal body containing a telescope and the large solar cell paddles. Body is just over five feet long.*

Robot Star Gazers

What does astronomy have to gain from space vehicles? The answer is the same as it was for solar physics. New dimensions of seeing: the X-ray and far ultraviolet regions of the spectrum and radio waves below about 20 MHz. There is, however, a basic difference between stellar astronomy and solar physics; the Sun is a single, big target, whereas the stars seem countless and it is difficult for unmanned satellites to find specific ones by remote control. The technical difficulties of stellar astronomy from space vehicles has caused this field to lag behind the other space sciences described earlier. Nevertheless, progress has been made with high altitude rockets and a few satellite experiments.

The study of cosmic X-ray sources is included in the category of space astronomy because there must be some astronomical object out there (not necessarily visible) that generates the X-rays. Actually, cosmic X-ray sources were reported as early as 1962 by R. Giacconi and his associates, who flew X-ray detectors in a rocket from White Sands, New Mexico. More rocket flights by other experi-



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menters have extended the list of sources to the point where scientists suspect that there are well over one thousand such cosmic X-ray machines. Just what these machines really are remains a mystery.

Some rockets have been equipped with ultraviolet instruments to see what stars look like at these wavelengths. T. A. Chubb and E. T. Byram have found that many stars seem strangely deficient in ultraviolet radiation. If one extrapolates the visible flux into the ultraviolet region, far more ultraviolet radiation is predicted than actually observed. This problem can be best approached by using a satellite with a stabilized telescope capable of making a large-scale survey of the heavens in the ultraviolet region of the spectrum. This is one of the major tasks of the Orbiting Astronomical Observatory (OAO) program.

Immense dish antennas are employed by Earth-bound radio astronomers to explore the sky at very long wavelengths. Radio astronomers, though, have always been frustrated by the ionosphere in their desire to pick up radio signals below 20 MHz. The first small satellites obviously could not carry dish antennas the size of a tennis court into orbit; but they did find room for small nondirectional radio receivers, which could listen to cosmic radio noise below 20 MHz. The U.S.-Canadian Alouettes, the Soviet Elektrons, Explorer XX, and many high altitude rockets listened at these low frequencies. Because they looked in all directions at once, these experiments could not pick out individual sources of noise. A general radio noise background was found for the cosmos. In addition, the Earth's ionosphere was found to be unexpectedly noisy. Beyond observations like these, the big discoveries in radio astronomy below 20 MHz will have to wait until highly direction-sensitive antennas can be placed in orbit.

NASA's initial answer to the problem of antenna directivity is the Radio Astronomy Explorer (RAE) which has ascended to orbit and deployed four straight antennas, each about 750 feet long. The antennas were made from beryllium-copper tape, which is rolled up prior to deployment. As the metal tape is paid out by a motor, it curls up into a long cylinder, which gives it rigidity. As the RAE orbits around the Earth, the directional antenna pattern sweeps the sky, picking up the low frequency signals that are absorbed by the ionosphere.

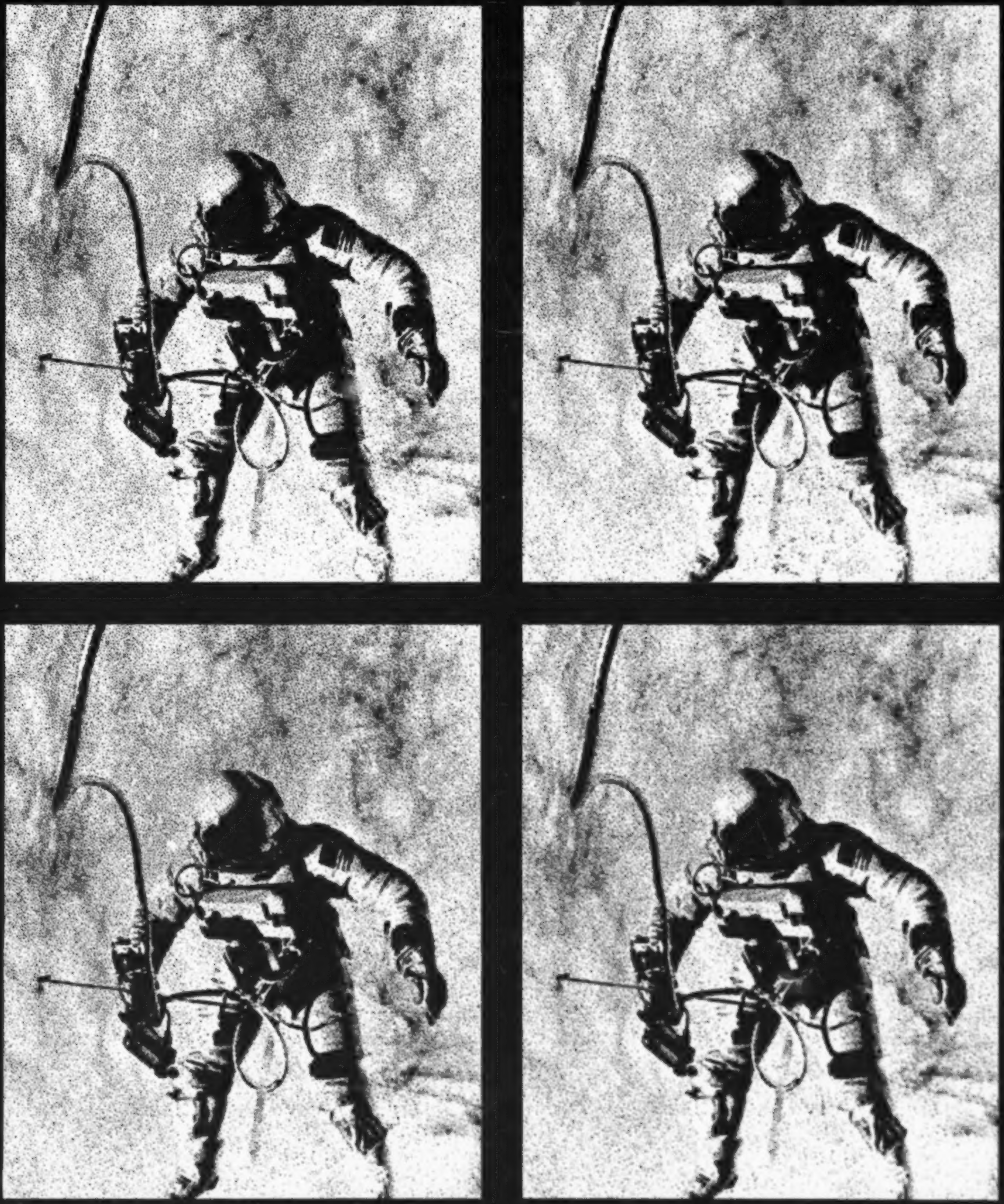
Our New View of the Universe

The great discoveries of space science; the Van Allen belts, the Earth's dust cloud, the magnetosphere, and the subtle and not-so-subtle influences of the Sun on the Earth were all made easier by the fact that rockets and satellites could carry instruments above the atmosphere. Eventually scientists might have been able to deduce the existence of these phenomena from purely terrestrial observations, but it might have taken decades longer. The sights and sounds of interplanetary space are so muffled by our atmosphere, ionosphere, and magnetic shell, that we have had to extend our senses with instrumented spacecraft to discover what really exists "out there." We have found a different universe, a universe more dynamic than we expected, one that seems rather alien at first. We have increased our understanding of the cosmos, and that is a prime purpose of science. Further, as we understand more about the forces affecting the solar system and the Earth, we are learning more about man's immediate environment and how to predict and control many of the forces which affect human life.

NASA-Langley, 1968

America In Space | The First Decade

Man In Space



National Aeronautics and Space Administration

America In Space: The First Decade

This is one of a series of booklets published on the occasion of the 10th Anniversary of the National Aeronautics and Space Administration.
These publications are not intended to be comprehensive history, nor do they deal with all the facets of NASA's aeronautical and space activities. Rather they are overviews of some important activities, programs and events written for the layman in terms of the several science disciplines.

Each of these subjects is treated in more depth in other NASA publications and in scientific journals.

1 October 1968

Titles in this series include:

I Space Physics and Astronomy
II Exploring the Moon and Planets
III Putting Satellites to Work
IV NASA Spacecraft
V Spacecraft Tracking
VI Linking Man and Spacecraft
VII Man in Space

Others are in preparation. Topics include:

Propulsion
Spacecraft Power
Space Life Sciences
Aeronautics
Space Age By-products
Materials

MAN
IN
SPACE

by David A. Anderton

National Aeronautics and Space Administration, Washington, D.C. 20546

Introduction

The first decade of the National Aeronautics and Space Administration is a story of accomplishment, combining great strides in science, technology, engineering and human experience. This is a chronicle of what is generally regarded as one of the most exciting and dramatic aspects of that decade, the NASA manned space flight program.

"Man in Space" covers the ground from those pre-Sputnik days when only a handful of scientists and engineers in the United States believed that man would *ever* fly in space, to the preparation for a manned lunar landing and return in this decade.

The account is, quite frankly, a thrilling one. It covers the adversities as well as the triumphs of Mercury and Gemini. It is a story of faith, dedication and perseverance, of heroic efforts by individuals and groups of men in many parts of the land. And, it notes the contributions of the NASA man-in-space program to science and technology and United States prestige and world leadership.

Soon Apollo, the greatest voyage of exploration ever undertaken by man, will add another chapter in the early years of the second decade of NASA. And after Apollo, and in the decades to come, other men will journey farther into space, for this is the certain destiny of man.

George E. Mueller
Associate Administrator for
Manned Space Flight

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Man In Space

Prologue

He steps off the ladder, very carefully, and his booted foot touches the lunar surface.

The rubble and the rocky moonscape seem familiar —they were simulated in his training program. The intense light and the blackness of the shadows are no longer strange.

He moves away from the ladder and the odd-looking craft standing with metallic legs a-straddle, and turns slowly for a look around his limited horizon.

A fast-moving, bright satellite swings into view, lifting rapidly above the horizon and toward the zenith.

But this time the satellite is no longer a projected image on the dome of a simulator. It's an orbiting spacecraft, standing by. The intense light is the Sun, not arc lights. And the rubble under his boots is truly the surface of the Moon.

He is the first American astronaut to stand there.

A few yards away inside the standing vehicle is a second astronaut, waiting his turn to step out of the lunar module. A third astronaut rides far above, orbiting the Moon and waiting for the coming rendezvous and the return flight to Earth.

This is an astronaut crew of the Apollo Program on the first United States manned lunar exploration mission. Drawn from the military services and civilian life, these astronauts fly under a single insigne: The symbol of NASA, the National Aeronautics and Space Administration.

The Apollo Program is one of the results of NASA's being. During the years since its formation, the agency has maintained a direct thrust toward the objectives of manned space flight, with lunar exploration as one of its goals.

And now, for the first time, that goal has been reached.

Minutes ago, the Apollo lunar module, a spidery-legged spacecraft, landed two of the astronauts on the Moon after an eight-minute descent—slowed by retro-rocket—from about ten miles above the surface. The final descent terminated a long coasting out of the 80-mile high lunar orbit, after one complete round trip of the Moon during which the crew transferred from the command craft and checked out the systems of the lunar lander.

Almost three days before, the astronauts had completed the maneuvers that separated, turned and rejoined the lunar craft to the combined Apollo command and service modules. During the three days of coasting toward the Moon, navigating, checking, observing, reporting, exercising, eating and sleeping followed each other in cycles through the space crossing.

Three days behind them lay the launch complex at Cape Kennedy, and the spent first and second stages *of the huge Saturn V rocket that had roared off the pad, urged skyward by seven and one-half million pounds of thrust.*

Apollo/Saturn V, as high as a 36-story building, weighing more than six million pounds, was topped by the command module, the only portion of that mammoth assembly that would return to Earth intact.

Behind the launching were months and years of work, studies and experiments by NASA and industry. Entire technologies had to be developed for the Apollo program. Two complete manned space flight programs—Mercury and Gemini—preceded it, and taught their valuable lessons. A huge launch complex, new test facilities, and new factories had to be built. One major new NASA center took form for the Apollo program, and other centers were expanded.

The Apollo command module topped more than just its Saturn V launcher. It was the apex of a vast pyramid of inter-related government agencies and private industries, universities and research laboratories, military services, small businesses, and knowledgeable individuals.

They were brought together under the management of the National Aeronautics and Space Administration, an organization that was hardly three years old when it was told to land men on the Moon, and given less than ten years to do the job.

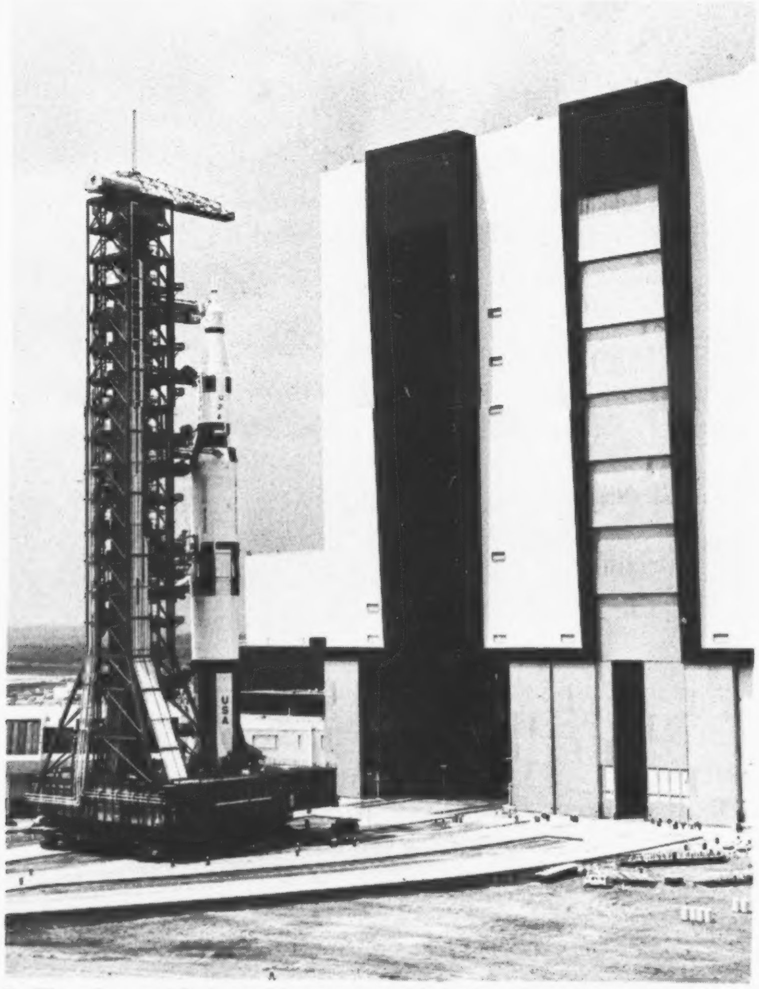
1 *NASA astronauts have accumulated many "space flight" hours in this Apollo mission simulator at the Kennedy Space Center, Florida. This simulator includes a command module and an accurate visual display of controls and instruments.*

The Apollo Program

Apollo started as a natural extension of NASA's manned space flight program. It was initially announced in mid-1960 as a program for sustained Earth-orbital flight, or a circumlunar voyage, carrying a crew of three astronauts.

But in May the following year, President John F. Kennedy set an extended goal for Apollo: "Now is the time to take longer strides — time for a great new American enterprise — time for this nation to take a clearly leading role in space achievement which in many ways may hold the key to our future on Earth . . .

"I believe this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to Earth. No single space project in this period will be more impressive to mankind, or more important for the long-range exploration of space; and none will be so difficult or expensive to accomplish."



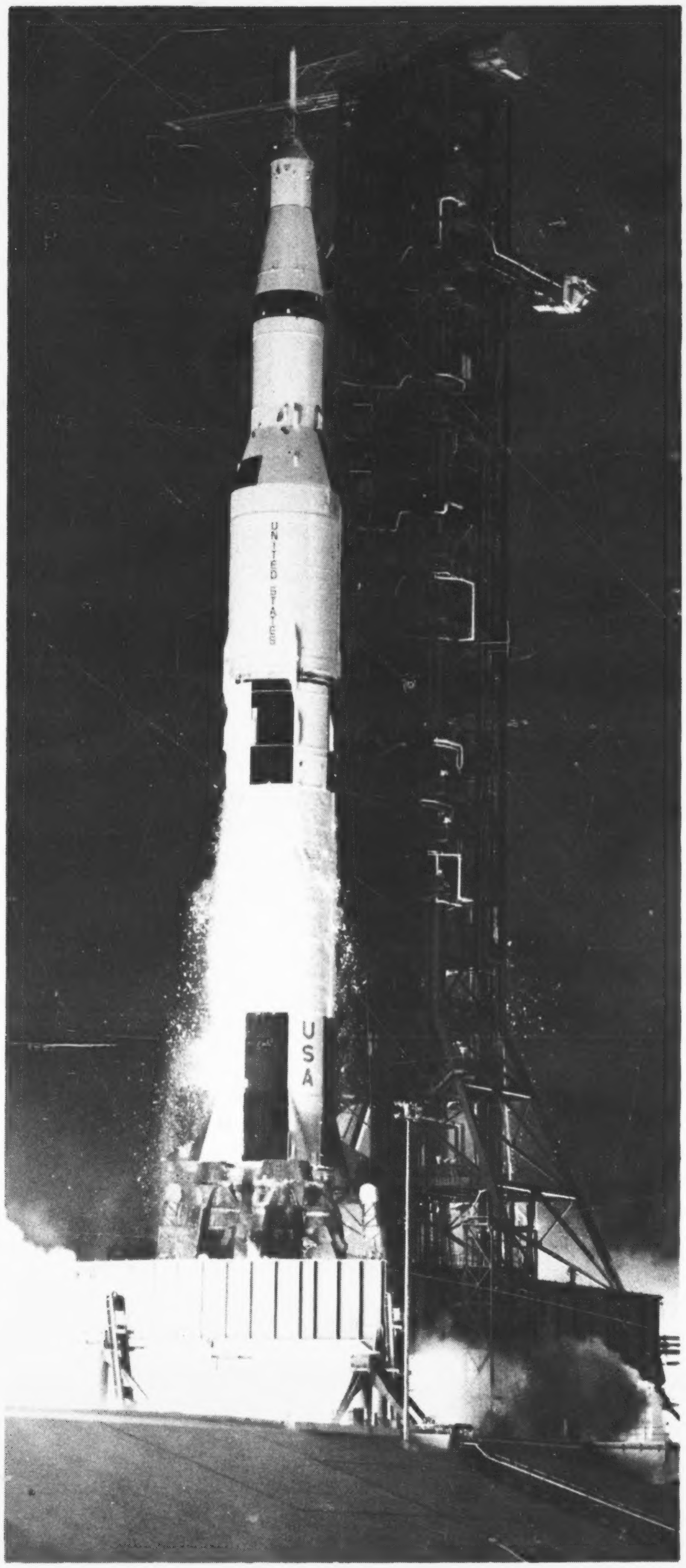
2 *The Apollo/Saturn V space vehicle leaving its assembly bay in the Vehicle Assembly Building (VAB) en route to Launch Complex 39.*

Those words defined a new goal for manned space flight programs, and described it as a national goal for the first time.

Kennedy's words were the formal announcement of a program that had been taking form for months. NASA scientists, engineers and administrators had been looking beyond the early stages of manned space flight, and the Mercury program which was then just getting manned spacecraft aloft. They saw the scientific advantages of a manned space exploration program, the national prestige such a program would confer, and the base of the national resources such an effort would build.

The lunar landing became a tangible symbol of this country's determination to succeed in space. Akin to the early voyages of discovery, Apollo's prospects would be much improved, and the aims of the program much better understood, if one result was a man stepping onto the lunar surface, like Columbus stepping onto the beach of the new world.

Apollo, like any other pioneering scientific program, had to wait for the availability of some of its technologies. Three men could not go to the Moon until men had tested themselves in more modest space flights.



3 The launch of NASA's second unmanned Apollo/Saturn V space vehicle from the Kennedy Space Center's Launch Complex 39, April 4, 1968.

Mercury And Gemini

NASA's manned space flight program started with Project Mercury, aimed at placing an astronaut in orbital flight around the Earth, investigating his capabilities while in orbit, and recovering him safely.

Mercury was seen as a necessary prelude to more extensive manned space flights, and originally was to be followed by the Apollo program for sustained flight in Earth orbit, and a trip around the Moon.

But two factors prevented the direct jump from Mercury to Apollo. As Apollo studies progressed, the gaps in available knowledge became apparent. Mercury had proved a lot about space flight, but it was not nearly enough to serve as the basis for a program of the magnitude of Apollo.

Further, when Apollo was first proposed, there were three apparent ways to make a voyage around the Moon. A direct flight from Earth was technically possible, but practically it would have required a gigantic vehicle. One alternative was to make multiple launches of smaller vehicles into Earth orbits, where they could rendezvous and assemble a spacecraft to make the trip the rest of the way.

A second alternative was to launch a spacecraft into an orbit around the Moon. A smaller spacecraft could be used to go from that orbit to the surface of the Moon and return to rendezvous before setting out on the voyage back to Earth.

Of the three possible procedures, lunar orbit rendezvous was considered to offer advantages of cost, schedule, simplicity, and minimal additional developments to be undertaken. It was chosen as the basic plan for Apollo.

But there was no available experience on rendezvous in orbit, which was the key to the success of the Apollo program. Further, there was a need to determine man's ability to withstand the rigors of the space environment and to develop all the techniques required for the lunar journey.

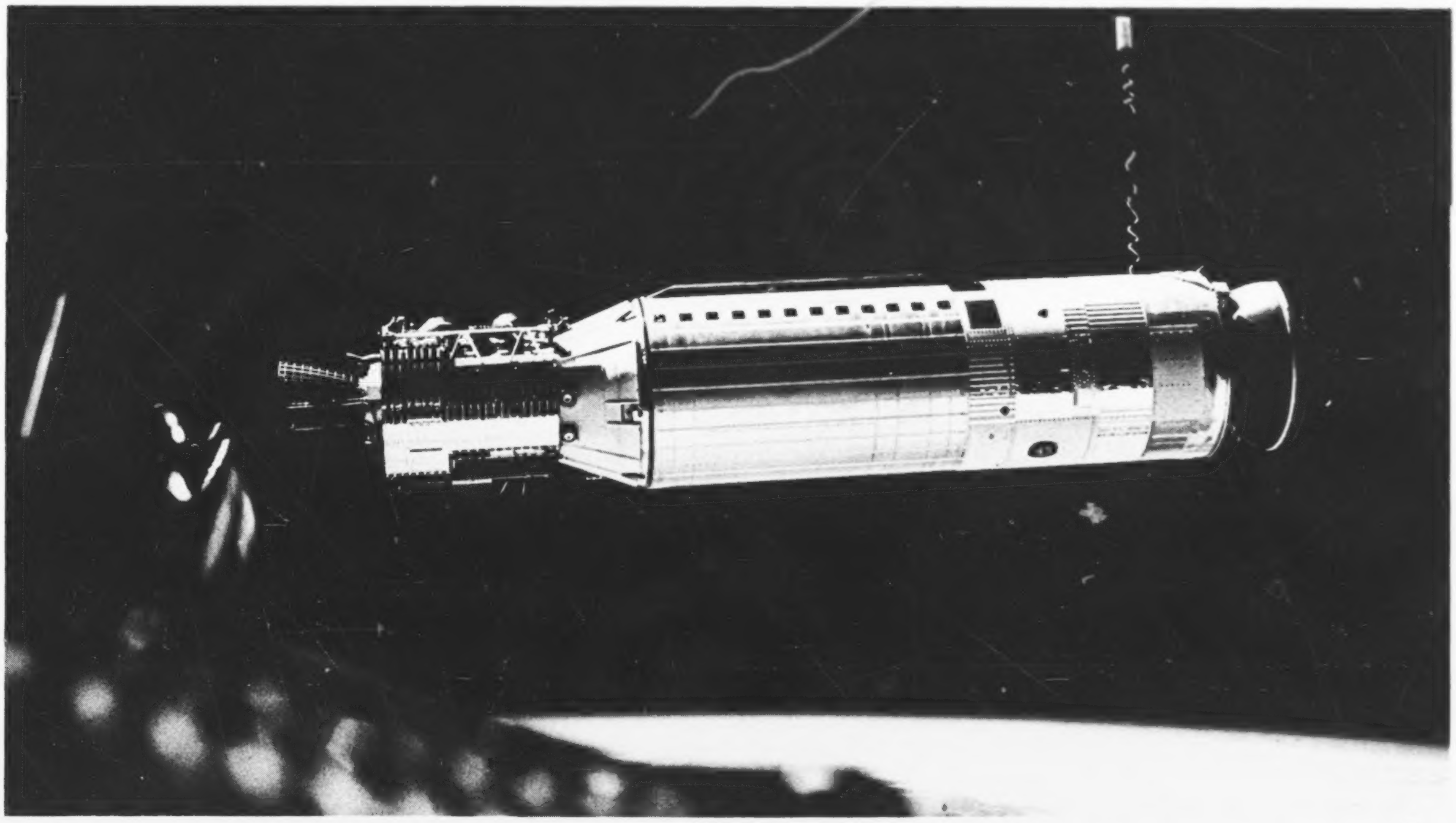
The Gemini program grew out of those needs. It served to bridge the gap in technology and operational know-how between Mercury and Apollo, and it developed the skills and assembled the flight crews, support personnel and facilities that would be needed when Apollo reached operational status.

A major contribution of the Gemini program to Apollo was the development and proving of space rendezvous techniques. Rendezvous were achieved under manual control by the pilots, and semi-automatically by the spacecrafts' systems. They were made from above and below the target vehicles, and early and late in the flight. In short, Gemini provided the experience in orbital rendezvous that had been lacking. Gemini also provided the long-duration experience, operational flight control procedures, ground crew skills, precise reentry, guidance and landing techniques, extra-vehicular activities and — most importantly — highly trained and experienced flight crews that would bring Apollo to its ultimate goal.

Milestones To Apollo

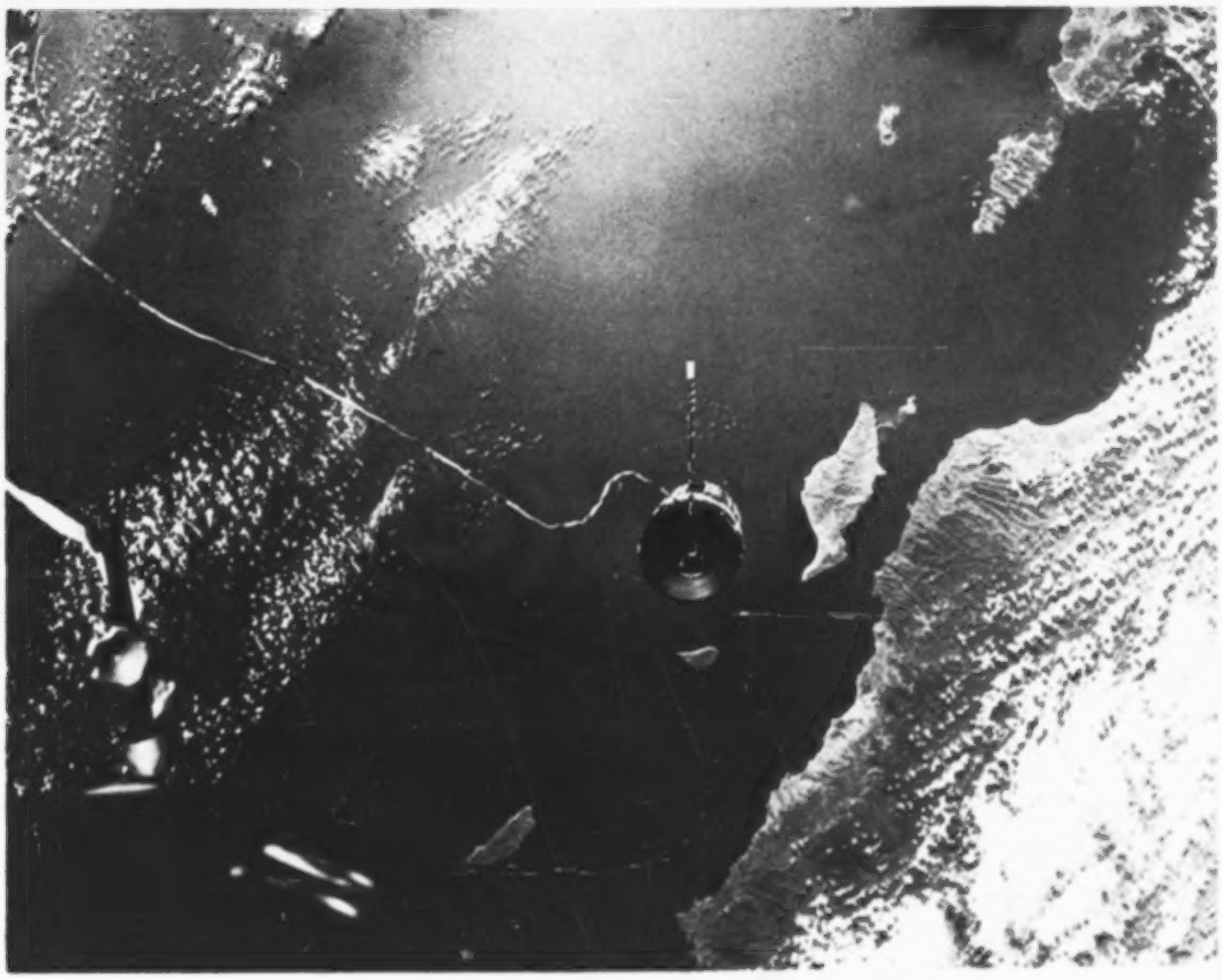
Tracing the road to Apollo could be like tracing the course of man's scientific and engineering achievements since he discovered fire and invented the wheel. But within NASA, and its predecessor organization, the National Advisory Committee for Aeronautics, there are some clearly defined guideposts which helped during recent years to point the way toward Apollo.

By mid-1952, there had been some serious proposals pointing toward the achievement of manned space flight. The Committee on Aerodynamics of the National Advisory Committee for Aeronautics, in a meeting June 24, 1952, resolved that NACA should " . . . devote a modest effort to problems associated with unmanned and manned flight at altitudes from



4 *Rendezvous with the Agena Target Docking Vehicle, as seen from the Gemini VIII spacecraft. Astronaut David Scott took this picture at a distance of 45 feet from the Agena spacecraft.*

5 *The Agena Target Docking Vehicle as seen from the Gemini XI spacecraft. The tether attaching the unmanned Agena to the two-man Gemini XI has just been jettisoned.*



50 miles to infinity and at speeds from Mach number 10 to the velocity of escape from the Earth's gravity."

Within days, three engineers from the Langley Memorial Aeronautical Laboratory, primary research center of the NACA, were asked by Langley's director to prepare proposals for manned space flight, and specifically, a start on development of a space vehicle within a couple of years.

Mid-1952 also saw the emergence of a novel concept for beating the heat of reentry. This was a question that was nagging the designers of ballistic missiles, faced with the problem of delivering the warhead safely through the atmosphere at near-hypersonic speeds. At NASA's Ames laboratory, a scientist developed a blunted shape, in complete contrast to the needle-nosed warheads advocated by the designers of ballistic missiles, and showed that the blunt shape would reduce tremendously the amount of air-friction heat that would have to be absorbed by the warhead.

Other NACA engineers at Ames laboratory had been experimenting with shapes for space flight. Winged and wingless shapes were analyzed for their behavior in reentry, hypersonic gliding flight, orbital travel, and interplanetary cruising.

The theory behind the blunt-nosed body and the experiments on the shapes at Ames began to coalesce in two concepts. One was a high-lift reentry glider which would behave like a ballistic shape in the first stages of reentry but would gradually develop lift as the atmosphere thickened.

The other was a purely ballistic capsule, which seemed like the simplest way to handle the reentry problem if the prospective astronaut could be supported properly to take the high loads of deceleration during the reentry.

These concepts were officially described by three Ames researchers early in 1954. They excited only a little interest; manned space flight was theoretically possible, but there was no urgency, no need to do it.

But on October 4, 1957, the Russians orbited the first man-made satellite of the Earth. Sputnik I burst open the door to the space age.

In retrospect, it seems that a long-planned NACA meeting provided the final nudge that got the manned space flight program going along its current route. There had been technical arguments between proponents of two different shapes for a proposed manned rocket-powered glider research aircraft, to be sponsored by the Air Force. To resolve these arguments, NACA proposed a conference October 15, 1958, at the Ames laboratory, to attempt to resolve the technical issue of whether the proposed hypersonic glider should have a rounded or a flat bottom.

At this conference, specialists in hypervelocity flight from Ames and Langley met and compared notes. They were agreed on one issue: For orbital flight the best design would be a blunted shape with a low lift-drag ratio. That way, the highest ratio of payload to total weight could be accommodated, and that was the nub of the man in space program.

Two of the Langley researchers returned from the conference convinced that it was mandatory to concentrate effort in order to achieve manned space flight as quickly as possible, and that this could best be done by concentrating on the ballistic capsule approach as a "best" spacecraft shape.

The hypersonic glider, either flat or rounded on the bottom, or the semiballistic body shape would take too long to develop. The best route to the stars would be mapped by a ballistic body, a blunt shape that would provide a maximum of protection for the crew in a minimum weight that could be lofted into space by an intercontinental ballistic missile, suitably modified and rated for manned flight.

6 *A view of Gemini VII spacecraft as seen through the hatch window of Gemini VI-A during rendezvous and station keeping maneuvers. Rendezvous was accomplished at an altitude of 160 miles on December 15, 1965.*

7 Astronaut Edward H. White is shown performing the Extravehicular Activity (EVA) portion of the Gemini IV flight. This 21 minute "space walk" was accomplished during the third orbit of the two-man spacecraft on June 3, 1965.

In the numbers of committees that were formed and met in the post-Sputnik days, there was one long-established group that had considered space flight as far back as 1952. The NACA Committee on Aerodynamics, meeting in late November 1957, adopted a resolution that asked for an aggressive program ". . . for increased NACA participation in upper atmosphere and space flight research."

But there were differences within NACA sparked by two views of the organization. One view was that NACA had a traditional role to fulfill, providing supporting research for projects conducted by the military services and industry.

The other view was the more radical one that NACA should grow to meet the new challenges of space flight. It should expand its traditional role and be willing to provide systems managers, directly guiding programs and actually performing the operational aspects of manned space flight, instead of leaving those tasks to others.

Officially, NACA espoused the former view. It looked as if this arrangement would be perpetuated when, in February, 1958, upon instructions from President Eisenhower, the Secretary of Defense ordered the creation of an Advanced Research Project Agency, with the mandate to manage all existing manned space flight projects, regardless of origin. Shortly after its formation, ARPA endorsed the Air Force's long-term responsibility for manned space flight and, in effect, established the USAF programs as the national effort.

Then on April 2, 1958, President Dwight D. Eisenhower sent a formal message to Congress in which he called for the establishment of a National Aeronautical and Space Agency (sic) which would take over NACA and also all the space programs except those primarily under development for the military. Subsequently, legislation was proposed, and Congress began hearings.

Even at this early date more than half of all NACA's activities were directed at space flight. NACA's top scientists and administrators had assumed creation of a national space flight program, and that NACA was the logical agency to handle it.

Spacecraft Development

Part of the NACA work had been presented in a paper by three Langley researchers at a Conference on High-Speed Aerodynamics held in March 1958. It was one of three papers at that conference which considered the alternative configurations for manned spacecraft, and it came down strongly on the side of the ballistic capsule approach.

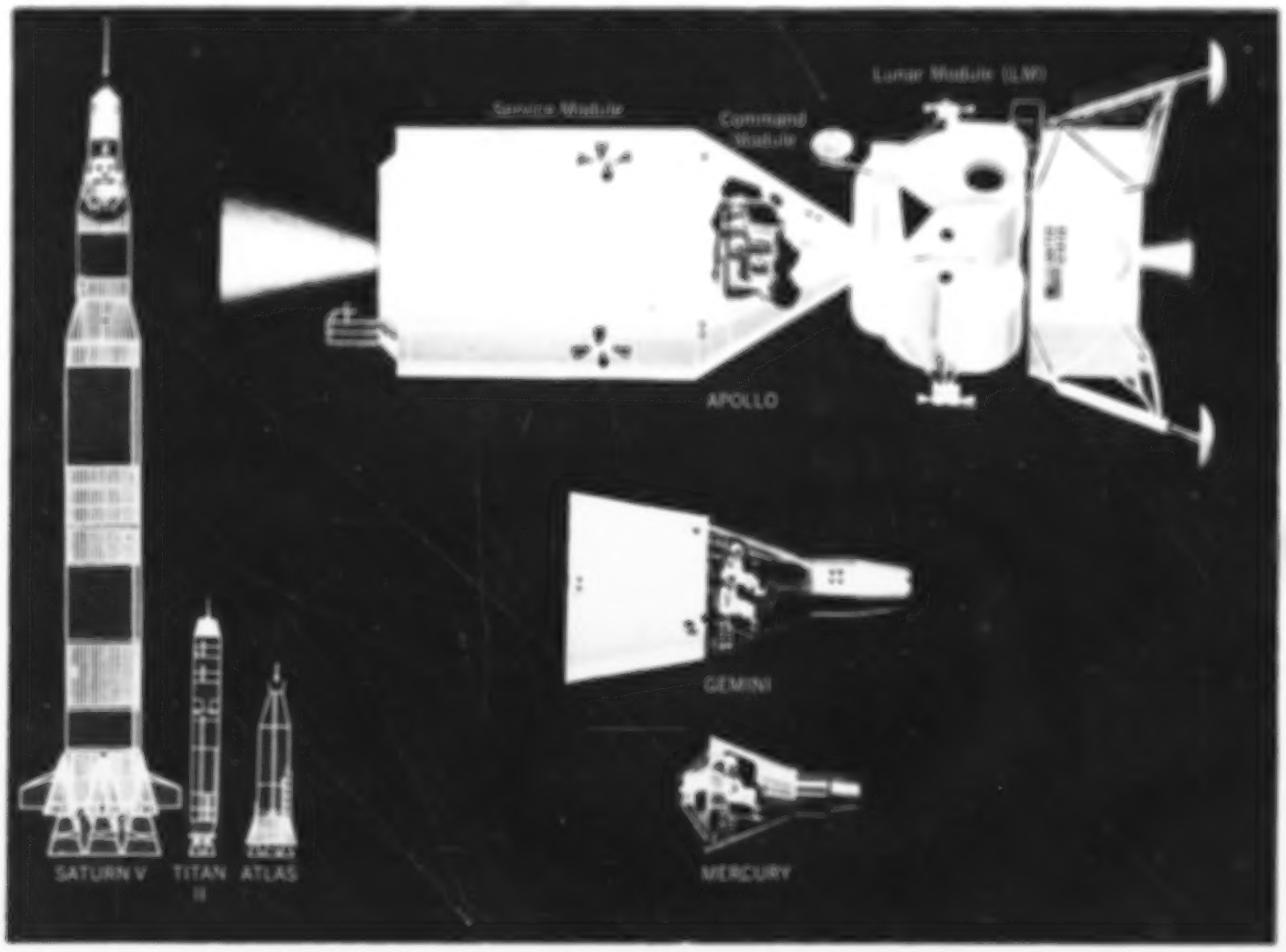
Such a route would be able to take full advantage of the ballistic missile experience that was then beginning to accumulate. A non-lifting vehicle could be brought back more easily by firing rockets that decelerated the spacecraft and deflected it out of orbit into a flight path of decreasing altitude.

The Langley presentation featured a conical craft with a flat heat shield; the astronaut's position would place him with his back to the heat shield at all times. This made it necessary to reverse the attitude of the spacecraft during orbital flight so that the reentry would be made with the heat shield facing the flight path to give maximum protection.

This method, the authors concluded, would make it ". . . possible to proceed confidently with a manned satellite project . . ."

As 1958 wore on, the researchers refined their conceptual design for a manned spacecraft, and it gradually evolved into the now-familiar shape of a rounded, blunt heat shield, a truncated conical body and a cylinder mounted atop the cutoff cone.

8 *Drawings indicate comparative size of Mercury, Gemini and Apollo spacecraft. Their launch vehicles are illustrated at the left: Mercury/Atlas, Gemini/Titan II and Apollo/Saturn V.*



The basic lines of that capsule were later adopted for the Gemini spacecraft, although a careful study of both configurations shows many differences in detail.

Apollo's conical command module, that will carry the three astronauts on their long trip to lunar orbit, seems like a reversion to the original layout considered for the Mercury project. It is about 12 ft. across the heat shield, and about the same distance to the apex of the cone. It weighs 13,000 pounds.

In contrast, the reentry module of the Gemini spacecraft had a diameter of about 7½ ft., stood almost 12 ft. high and weighed about 4,800 pounds. The Mercury reentry capsule had a six-foot diameter, was about seven feet high, and weighed about 3,500 pounds.

Two other novel ideas took shape during 1958. There was an obvious need for an escape system of some kind, if there should be trouble during the launching. NACA engineers thought of using solid-propellant rockets to pull the manned capsule away from the launch vehicle, instead of pushing it away as in conventional aircraft escape systems. The escape tower resulted; the structure topped the space capsule with a framework that held a rocket motor with canted nozzles to discharge the rocket blast away from the spacecraft.

The second idea was for crew protection during reentry, when the decleration forces could mount to as high as 20 times the force of normal gravity. An NACA scientist thought of a simple lightweight couch, made of fiberglass and contoured to fit the individual. By supporting him over as much of his body surface as possible, the total load would be distributed evenly.

The prototype couch was made and tested; two test subjects withstood more than 20 times the force of gravity.

9 *Astronaut John Glenn climbs aboard his Friendship 7 spacecraft prior to his historic three Earth orbit mission on February 20, 1962.*

UNITED
STATES
Friendship

The National Aeronautics and Space Act of 1958, signed into law by President Eisenhower on July 29, 1958, was the basis for establishment of the National Aeronautics and Space Administration.

NASA's first administrator, T. Keith Glennan, said in a communication to NACA personnel, just before the changeover from NACA to NASA, that it was a metamorphosis that was taking place. And he added, "We have one of the most challenging assignments that has ever been given to modern man."

He had, as a nucleus for that metamorphosis, researchers in space flight from Langley, its associated Pilotless Aircraft Research and Flight Research Divisions, and Lewis. They were officially named the Space Task Group in November 1958, and they served as the nucleus of the much larger organization to come.

Actually, the official sanction confirmed what had been happening for some months. Earlier that year, some engineers from the Lewis research center had joined the Langley group, lending their expertise in structures and thermal protection. The work of the informal group had reached such a level that they were able to request proposals from industry for a manned spacecraft, before official recognition of the Space Task Group.

The major technical decision still pending was the final choice of heat shielding. The designers of ballistic missiles had extended the blunt-body approach into two subsidiary fields. In the first approach, they had built the blunt body out of a material, like copper, that could withstand high temperatures and in effect store the heat of reentry. This is often called the heat-sink approach.

The alternate was to use material like nylon or Teflon, that vaporized under the extreme temperatures and carried heat away from the shield in that vaporization process. This generally is called the ablation technique. Neither method then showed a clear advantage, and so the decision was deferred until the last possible minute.

Later, after carefully monitoring technical progress with both types of shields, NASA engineers selected the ablation technique to protect the Mercury astronaut.

There was one last consideration: Name the project. From a final short list of designations, Project Mercury was chosen to be the popular name. Mercury was the Roman messenger of the gods, and his name seemed a suitable choice.

Project Mercury was formally announced as the name of the first NASA manned space flight program on December 17, 1958, the 55th anniversary of the first flights of the Wright brothers.

With a formal project name, an organization, and some of the major technical decisions behind it, Project Mercury was under way.

10 *Launch of the first United States manned Earth orbital flight at Cape Canaveral (renamed Cape Kennedy), Florida on February 20, 1962. The Friendship 7 Mercury spacecraft, perched atop its Atlas launch vehicle, carried Astronaut John Glenn on his three orbit mission.*

GOOD LUCK
FROM
2ND SHIFT
NASA

11 *Technicians make last minute checks before sealing the hatches of the Gemini VI spacecraft. This two day mission began for Astronauts Walter M. Schirra, Jr. and Thomas P. Stafford on December 15, 1965 and included a rendezvous with Gemini VII.*

Launch Vehicles

The Mercury program, planned to get man into space in the minimum amount of time, made use of available systems and components wherever possible. The crew capsule had been designed to weigh about the same amount as a standard warhead for the ballistic missiles then under development, following the reasoning that it was inevitable that those missiles would be used, in slightly modified forms, as the launchers in the Mercury program.

For the sub-orbital Mercury flights, the Redstone missile was chosen as the launch vehicle.

The basic missile was modified by extending its cylindrical tankage section to include more fuel for increased cutoff velocity. Simplifications were introduced to increase the potential reliability of the launcher, and an adapter was designed and built to match the Mercury spacecraft.

In its final form, the Redstone launch vehicle stood 59 ft. high from the base of its fins to the frame that held the spacecraft. The Mercury capsule and escape tower added another 24 ft. to the height of the assembly.

For the orbital flights in the Mercury program, more power was necessary. The Air Force Atlas ICBM had been tapped for the second phase of the Mercury launches. It had the potential to do the job, and it had Air Force support behind it, determined to make it a reliable operational weapon.

The D model Atlas was chosen, and was modified An abort sensing system was developed and installed as additional protection for the astronaut. The posigrade rockets, used to guarantee separation of the warhead, were removed because Mercury carried its own rockets to aid separation.

The final Atlas launcher configuration resembled the standard missile right up to the part where the warhead would have been mounted. At that point there was an adapter that held the Mercury spacecraft and escape tower. The assembly stood over 95 ft. tall ready to launch.

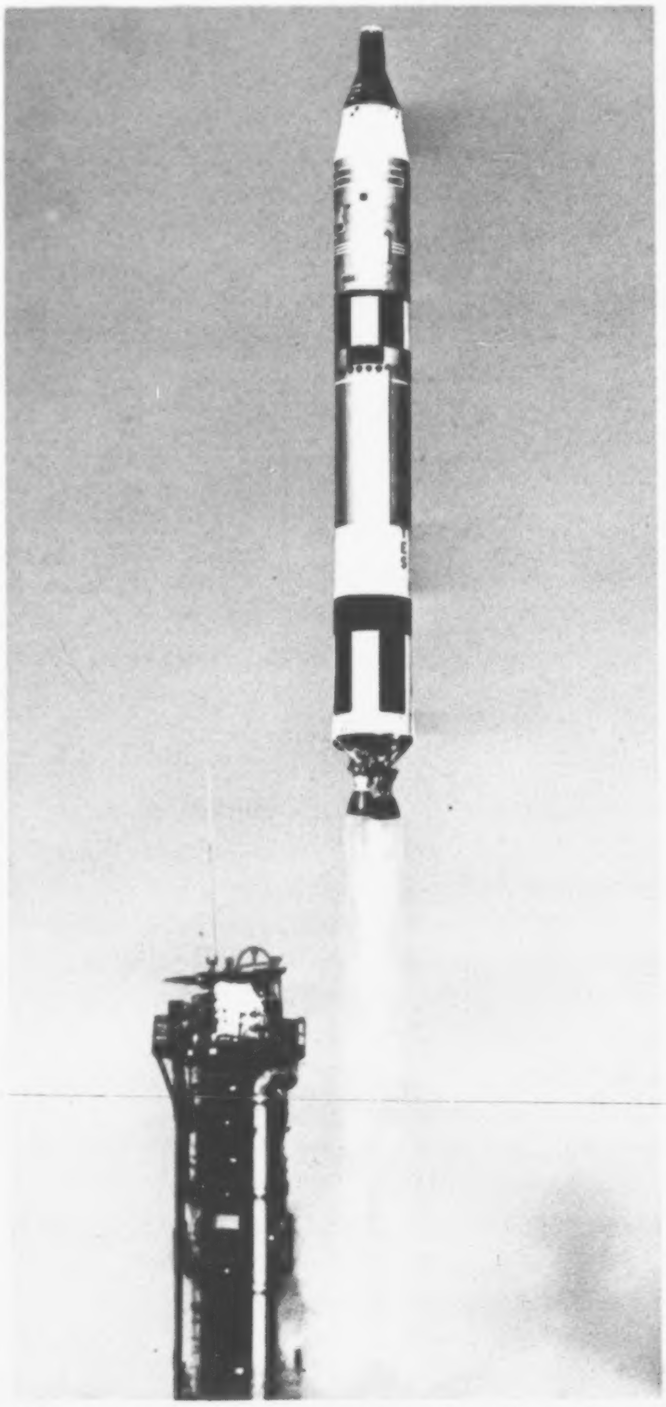
As the outlines of the Gemini program emerged, the need for a new launch vehicle became obvious. Again looking for economies, NASA surveyed the missile field.

The choice was the Titan II, an operational model of the intercontinental ballistic missile. Titan II carried a much larger payload than the Atlas had carried, and could handle the larger Gemini spacecraft. Also, Titan used a propellant combination that could be stored, in contrast to the liquid oxygen in the Redstone and Atlas missiles, which boiled off during lengthy delays in firing and had to be continually topped off to maintain fuel capacity.

The changes to Titan II involved mostly modifications and simplifications rather than construction of any major new components. However, redundant or backup systems were added to improve flight safety. Thus man-rating the vehicle for the Gemini program involved significant improvements in reliability of components and systems. The engines and their control systems were augmented. The missile's inertial guidance system was replaced with a radio type. Backup systems capabilities were added to the flight-control and guidance system. A malfunction detection system was added.

The two stages of the Titan II launcher towered 90 feet above the pad, and the space craft added another 19 feet.

Apollo demanded another order of magnitude in booster power. Here again, developmental work was already in progress when NASA began its man-in-space program. The Army Ballistic Missile Agency



12 *The Gemini XII launch from Cape Kennedy; final flight of the Gemini series. Astronauts James A. Lovell, Jr. and Edwin E. Aldrin begin a four day flight that will see Aldrin spend 5 hours and 37 minutes outside of the spacecraft in EVA (Extravehicular Activity).*

13 *After their successful 25 hour 52 minute Earth orbital flight, the crew of Gemini VI-A—Astronauts Walter M. Schirra, Jr. and Thomas P. Stafford—await recovery by the aircraft carrier USS Wasp.*

14 *Firing Room 2 during the Apollo VI mission at the Kennedy Space Center's Launch Control Center.*

had been working on a booster called Juno, with definite potential for space flight. The technology of the Juno booster led directly to Saturn I.

Saturn IB, the next stage in the development of the Apollo launch vehicles, uses the first stage of Saturn I, but has a new second stage with a single liquid hydrogen engine which is more than twice as powerful as the six clustered engines in the second stage of Saturn I.

The mission of Saturn IB is to carry unmanned and manned Apollo spacecraft into Earth orbit as preliminary flights before the Moon voyage.

Saturn IB weighs about 1.3 million pounds and stands 141 feet high. First launched February 26, 1966, the launch vehicle had flown four successful missions in as many tries by early 1968.

The Saturn V vehicle, which will launch the final round of Apollo missions toward the Moon, dwarfs all the other launch vehicles with its 282-ft. height and its lift-off weight of more than six million pounds.

Five F–1 powerplants, producing a total thrust of 7.5 million pounds, furnish the main thrust. They and their tankage volume constitute most of the first stage of the Saturn V. The first stage is topped by an interstage, which contains ullage rockets — fired to accelerate the second stage a little so that the fuel will start to feed in the absence of gravity — and the first-stage electronics.

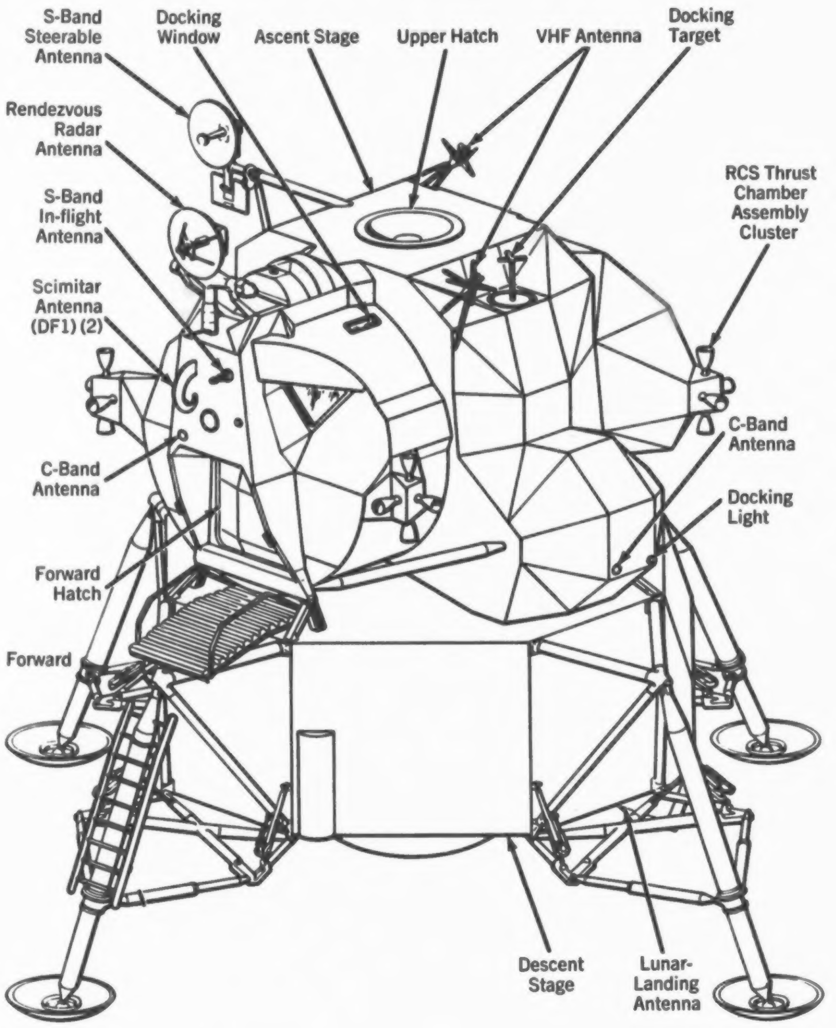
Above the interstage is the second powered stage, with a cluster of five J–2 engines which develop more than one million pounds of thrust. Liquid hydrogen and liquid oxygen are the propellants.

The third powered stage contains a single J–2 engine, its controls and tankage. An instrument unit and a truncated conical housing, which holds and protects the lunar module during flight, tops the third stage.

On top of this is the service module, which holds fuel cells for electrical power in space, tanks and supporting systems. It is powered by a single restartable engine that can be fired repeatedly in the space environment. It carries the burden of propulsion and maneuvering the spacecraft after the third stage of the rocket has been jettisoned.

Above this is the command module and the escape tower, the crews' quarters and their emergency exit in the event of trouble on or near the pad.

15 *The lunar module (LM) which will carry the two Apollo astronauts to the surface of the Moon.*


S-Band Steerable Antenna
Docking Window
Ascent Stage
Upper Hatch
VHF Antenna
Docking Target
Rendezvous Radar Antenna
S-Band In-flight Antenna
Scimitar Antenna (DF1) (2)
RCS Thrust Chamber Assembly Cluster
C-Band Antenna
C-Band Antenna
Docking Light
Forward Hatch
Forward
Descent Stage
Lunar-Landing Antenna

Test Vehicles

Before manned spacecraft could be lofted into space, hundreds of tests had to be made on the ground and in flight. Some of these could only be made in the real environment of space, in orbital or sub-orbital flight; they would require as complete and complex a launch vehicle as the manned flights themselves.

But there were other flight tests that didn't require either the complexity or the capabilities of the space launch vehicles. For making those tests, NASA engineers developed or modified a series of rocket-powered test vehicles.

First of these was Little Joe, a cluster of four Sergeant solid-fuel rockets, with an altitude performance that approximated the proposed Redstone launch vehicle. It could do a variety of jobs, cost about one-fifth of the cost of an operational Redstone, was cheaper to operate, and could be fired from the Wallops Island facilities.

Eight Little Joe shots were made during the Mercury program, checking abort procedures and the functioning of the escape system, proving the spacecraft aerodynamics and integrity, launching primates, and qualifying the spacecraft at maximum dynamic pressure.

Inevitably there was a Big Joe, the only one of its name, to do a single job that the Little Joe vehicles couldn't do. Big Joe was the sixth Atlas D to be fired, and it was to carry a boilerplate spacecraft in a test of the ablative heat shield principle.

There had been a technical argument since the beginning of the Mercury program over the relative merits of heat-sink and ablative techniques for beating the heat of reentry. Space Task Group, after hearing both sides, and after waiting as long as possible because of the uncertainties, had come down in favor of the ablation technique.

Big Joe was planned to check the ablative properties of a new heat shield design for Mercury, and a lot was riding on the result of the test.

There were two points to be proved. The first was the efficiency of the heat shield and the ablation technique. The second was the inherent dynamic stability of the spacecraft shape, which was expected to be able to re-orient itself to place the heat shield forward in its flight path. Both points were proved by the single Big Joe shot.

The Gemini program didn't use test vehicles of the Little Joe or Big Joe category, but it did depend on the availability of a target vehicle for rendezvous on several missions.

This target was the Atlas-Agena vehicle, a combination of two tested, high-performance, rocket-powered vehicles developed originally for the Air Force. The Atlas missile first stage was essentially the booster of Project Mercury, with some difference because of the differences in mission.

The upper-stage Agena D was the actual target stage. It was powered, could maneuver in orbit, and was designed to enable the Gemini spacecraft to dock and maneuver with the target.

For Apollo, the Saturn I test vehicle was developed, drawing on the Army's background in its work with the Jupiter-C, a reentry test vehicle.

The first stage of Saturn I was like a group of Redstone rockets fastened together. It used eight Redstone rocket engines, each complete with a fuel tank which was the same diameter as the fuel tank on the Redstone. These were clustered around a single liquid oxygen tank which was the same diameter as the tank section of the Jupiter missile.

A decision had been made by NASA to use liquid-hydrogen fuel as the upper stage propulsion system in the Apollo program, so the second stage of Saturn I was redesigned around a cluster of six RL10 hydrogen engines.

Above this stage was an instrument and guidance unit, and then a skirt with the transition piece to the payload.

This booster was to launch various Apollo tests, as well as to carry three large Pegasus micrometeoroid detection satellites into Earth orbit to check the possibility of micrometeoroid hits on future spacecraft.

In its final form, the Saturn I launch vehicle weighed more than one million pounds, stood about 190 ft. high, and had a payload capability of 39,100 pounds in near-Earth orbit.

Ten Saturn I missions were flown, and all ten were successful.

Astronauts For Space Flight

The job of selecting volunteers for the manned space flight program demanded early attention by the Space Task Group. They consulted with aeromedical specialists and evolved a plan of action for establishing the pool of astronaut candidates. Criteria were developed, and the general plan was to select six men, winnowed down from 12 who had been chosen to be trained, out of 36 who had been tested, out of 150 who had been nominated by industry and the military.

But President Eisenhower made the final choice of method by deciding, during the last weeks of 1958, that the jobs would be filled by candidates chosen from the existing pool of military test pilots. The long list of criteria in the original work statement dwindled to seven principal points: The candidates had to be under 40 years old, under 5 ft. 11 in. tall in excellent physical condition, graduated with a bachelor's degree or to have acquired the equivalent education, graduated from test pilot school, have had 1,500 hours minimum total flying time, and qualified in jet aircraft.

The final selections turned up seven names, when six were desired. All seven candidates were equally well qualified, all wanted to volunteer, and so NASA finally decided to name seven astronauts for Project Mercury.

The first seven, whose names were to become familiar throughout the world, were announced in April 1959.

Senior in age and date of rank was Marine Lieutenant Colonel John H. Glenn, Jr. Lieutenant Commanders Walter M. Schirra, Jr., and Alan B. Shepard, Jr., and Lieutenant Malcolm Scott Carpenter came from the U. S. Navy. Captains Donald K. Slayton, Leroy Gordon Cooper, Jr., and Virgil I. Grissom were from the Air Force. They were the first of America's astronauts, now numbering more than 50.

The second group was named in September 1962, and the third in October the following year. The latter were required to have higher academic qualifications, but the requirement for pilot training was reduced.

The first scientist-astronauts were selected in June 1965, and no piloting experience was required. However, if they weren't pilots, they did receive flight training. The list was narrowed from 422 applications to six selected.

A fourth group, this time of 19 astronauts, was announced in April 1966, all of them qualified jet pilots. In 1967, the National Academy of Sciences nominated a second group of scientists for training as astronauts, which produced eleven astronauts-to-be, with doctorates in science.

The initial emphasis on pilot ability in choosing astronauts from the top level of the nation's test-pilot force underlined another of the fundamental decisions of the NASA manned space flight program. In most of the early proposals for space flight, there had been almost universal acceptance of the crewman as a passenger, with nothing to do but survive the strange environment.

NASA's view was different. One of the objectives of the Mercury program was to find out what man's capabilities were in space flight. There would be plenty for him to do, and not just in the line of busy work, either. He could be a useful communications link; he could change the attitude of the spacecraft; in the event of failure of any automatic system, he would be able to take control and to complete the mission.

The importance of keeping the man in the loop, as most engineers called the concept, was followed through in the engineering design of Mercury. Manual control capability was built into the spacecraft, giving the astronaut pilot an override of many automatic features.

This paid off later in the Mercury program. In each one of the orbital flights, there was some kind of system malfunction which could have compromised the mission.

Astronaut John Glenn, in the MA–6 mission, was plagued with three malfunctions, one of them being the failure of the control system thrusters. He was able to fly manually to complete the planned three orbits. If the astronaut had not been in the control loop, the mission would have been aborted after one orbit.

But potentially most dangerous was the erroneous signal given the ground that Glenn's heat shield had released. If the heat shield release had been triggered, the subsequent automatic jettisoning of the retro-rocket package, which was literally strapped across the heat shield to the spacecraft, would have detached the shield and the spacecraft would have burned during reentry. Glenn was told to override the automatic jettisoning of the retro pack and to make his reentry with the pack in place. He did so, and the mission was a success.

Astronauts Schirra in MA–8 and Cooper in MA–9 also were able to override an automatic system that had malfunctioned. Schirra's was in his suit, which started to show an increase in temperature from the automatically reduced flow of coolant. Manual control of the coolant valve corrected that fault.

Cooper was able to fly his spacecraft manually during retro-fire and reentry after the automatic control system developed short circuits and malfunctioned.

Pressure Suits

The Mercury astronauts wore a pressure suit that would inflate and sustain them in an emergency such as a loss of pressure in the spacecraft cabin. Development of these suits had been helped immeasurably by advanced designs for Air Force and Navy pilots who were flying high-altitude missions routinely. But these suits were not adequate for the extreme altitude protection demanded by the Mercury project. Further, the suits had to be integrated more closely than ever before with the environmental control system used in the spacecraft.

As finally worn during the Mercury flights, the pressure suit was a modification of a fairly standard item, the Navy's Mk. IV full-pressure suit. The suit was under continuing development for the duration of the Mercury program.

Work was aimed at making the suit more comfortable, because it had to pressurize the astronaut. Under pressure, the suit stiffened, and relative immobility was the result. Chafing and pressure points made the suit uncomfortable. Every time the suit was worn, it was stretched out of shape, and fit worse as time went on.

Continuing development resulted in a suit that was wearable, if not exactly relaxing. It was to be further modified in later space flight programs, but for the time, and for Mercury, the suit was adequate for the job.

The same approach was used during the Gemini program. By then, the pressure suit had evolved to an item quite different from the Mercury suit. The basic suit was a four-layer garment with oxygen ducting for breathing and ventilation. It was used successfully on the short-duration missions. But for the fourth Gemini flight, when extravehicular activity (EVA) was programmed, the suit had to be modified further.

The EVA suit had added layers of material to protect the astronaut from micrometeoroid hits while he was outside the spacecraft, and to give him more thermal protection. The helmet had a second visor, intended for use only outside the spacecraft, to give extra protection from the sun and to protect the inner visor from any possible impact damage.

This suit also was generally satisfactory, although crew reports noted that the comfort was marginal for long-duration wear inside the spacecraft.

Consequently, a new suit was designed just for the planned 14-day Gemini VII mission. It was a "soft" suit, with a fabric hood which could be removed for storage. Being lightweight, the suit gave a maximum of freedom and comfort to the astronaut.

That suit met its design requirements But the reports of the Gemini crews pointed to one fact: The most comfortable suit was no suit at all. When they took off their pressure suits, they slept better, felt more comfortable and perspired less. They recommended that suits be removed in all long-duration space flights.

The plan for Apollo is to take into account the recommendations of the Mercury and Gemini crews. Basically, the Apollo astronauts will live and work in a shirt-sleeve environment free of the encumbering pressure suits except for critical phases of the mission.

The shirt-sleeve suit actually is a constant-wear garment, with a helmet for communications equipment.

The pressure suits will also have a portable life-support system worn as a back pack, which will sustain the astronauts for up to four hours on the lunar surface.

Space Medicine

With men on board the spacecraft, attention turned towards the disciplines of space medicine. Space flight was known to present new hazards to human life, but the degree of danger was not well defined. Radiation at high altitudes had been noted as a problem years earlier, in manned balloon flights to then-extreme altitudes, and in rocket-borne experiments with simple biological subjects.

Weightlessness was a big unknown. There were no long-term data, and no way of getting them in any simulated situation on Earth.

The environmental stresses of noise, vibration, g-loads, temperature and other characteristics of launch and space flight were thought to be problems. The astronaut would be under mental stresses that were new, as a result of his environment. Loneliness might be a major complaint. Toxic or noxious fumes at best would be annoying and at worst might imperil the astronaut.

These questions had to be thoroughly researched. Further, these answers would hold the key to all future space exploration. The difference between short-term exposure and long-term exposure to hazards might mean the difference between the success of a Mercury mission and the failure of an Apollo flight.

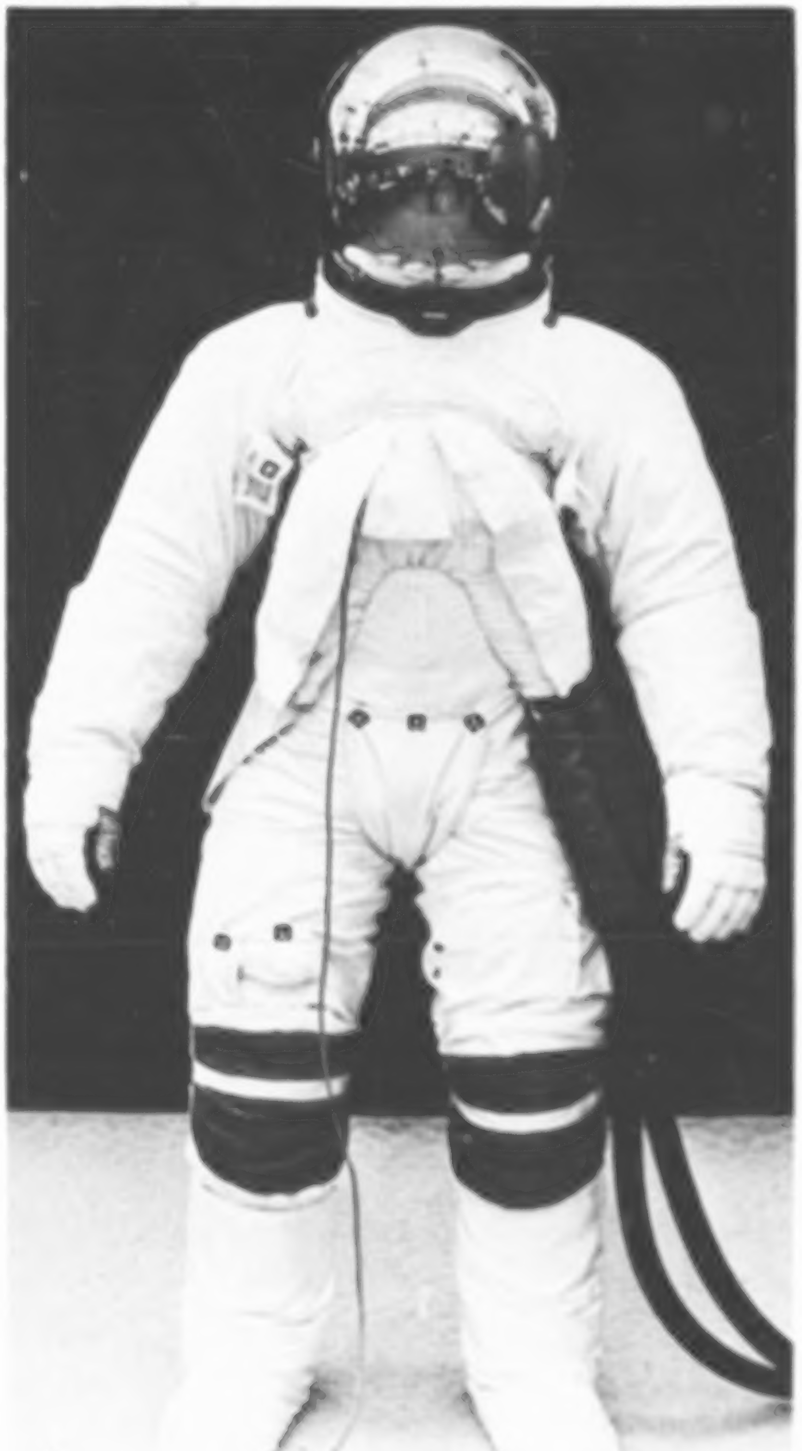
In March 1960, NASA established its first Office of Life Sciences, with long-term goals related to the exploration of space and the possible effects of the space environment on biology.

Capability for some aspects of space medical work, particularly in the engineering of life-support systems, had been developed early by the Space Task Group. Work on astronauts' suits and life-support systems was well along.

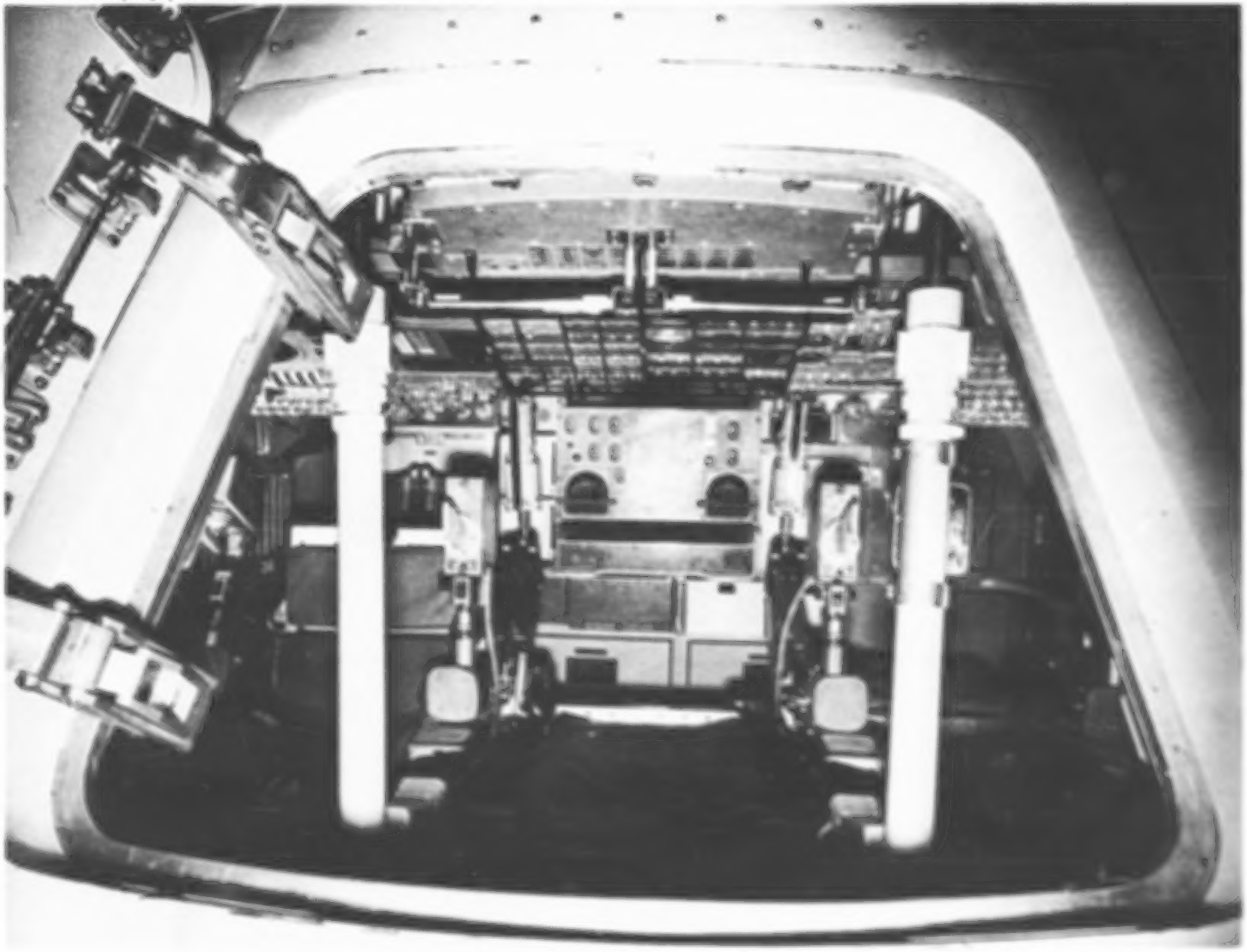
But there was a long-term need for biomedical scientists to plan solutions to the problems of future extended manned space flights, to watch over man as a passenger and crewman, and as a stranger visiting another planet.

NASA's Office of Life Sciences tackled the long-term job and stood ready to help with Mercury as needed.

16 *A test subject models the uprated A6L Apollo pressure suit that will be worn by NASA astronauts on their lunar mission. The outer surface of the suit is of Beta fabric and the patches on the shoulders, elbows, knees and back are of metal fiber cloth. The suit is intended to be worn during pre-launch, launch and reentry phases of the mission. It is fire-resistant.*



17 *Mock-up of the Apollo spacecraft, as seen through the hatchway. Below are the three astronaut couches and the main display panels.*



The basic space medicine approach to Project Mercury was to try to learn everything possible, and so the doctors decided to instrument the astronauts thoroughly. There was one ground rule, which eliminated any surgical implants of sensory instruments. All medical measurements were to be made with externally mounted sensors.

Unfortunately, there were no reliable off-the-shelf sensors that could be used in space flight measurements. They had to be developed for the Mercury flights, and modified as analysis of data indicated the need.

Breathing rate, heart rate and rhythm, blood pressure, and body temperature were the basic parameters monitored during Mercury flights. That in-flight data, coupled with careful control of the astronauts' diets before flights and extensive pre- and post-flight medical examinations, gave the Mercury doctors quantitative effects of space flight.

One of the more valuable medical parameters was voice transmission from the astronaut to ground stations. This had been anticipated as interesting, perhaps even vital data, and so a medical flight controller was an early member of the flight control team. By listening carefully to the astronauts' transmissions, the medical flight controller could evaluate the astronaut. His voice and answers to key questions from the medical monitors were factors in determining his condition.

Pre-flight and post-flight medical observations in the Mercury program were concerned with monitoring the condition of the astronaut, and the changes that occurred during space flight. Post-flight urinalysis and blood tests furnished valuable data on changes in body chemistry.

There was another and equally important post-flight task. Medical aid had to be available immediately to the recovered astronaut if he were to require it. Again, the level of knowledge at the beginning of the Mercury programs was unable to predict what effects the strain of reentry and recovery might have when superimposed on the long period of weightlessness in orbital flight. There was a chance that the effects could be harmful; but it was certain that the effects woud be interesting, medically speaking, and so medical teams became part of the recovery forces. Their job was to provide quick medical aid, and to conduct, promptly after recovery, the detailed physical examination to determine changes during flight.

Mercury proved that an astronaut could perform in space flight without any serious changes in his normal bodily functions for about one and one-half days. There was no evidence of any abnormal psychological responses.

The astronauts could sleep in orbit, although there were some subjective comments about that. Some said that their arms, floating in weightlessness in an unaccustomed position, woke them up.

The early fears of radiation damage failed to materialize. The primary reason was that the flight path was below the altitude limits of the Van Allen radiation belt around the Earth. Some form of radiation measurement was included on all Mercury flights, but when a man-made radiation belt was detected before the MA–8 flight, dosimeters were added to the astronaut and spacecraft medical instrumentation. But both that flight and MA–9 showed less radiation received by the astronauts than they would have received during a routine chest X-ray.

There was an expected response to the stress of launching and reentry, anticipated by the doctors and psychologists who had helped plan the Mercury medical operation. These showed as increased heart and respiration rates, a very normal reaction by a human under stress. But what was normal for the astronauts was previously thought to be abnormal; their pulse and respiration rates exceeded previous normal experience. Pre-flight test data had proven that the previous limits were in error, and a healthy male subject under stress did extend the range of normal behavior of the heart and lungs.

The acceleration of launch and the deceleration of reentry were tolerated by the astronauts. True, they were in superb condition from training and experience, but the forces were higher, particularly on reentry, than routinely experienced.

Finally, the experience gained in medical planning and monitoring during all phases of the Mercury program proved invaluable. Modified and adapted to Gemini and Apollo, that experience has become part of the increasing background in space medicine.

A new medical factor was introduced on the Gemini flights: Extra-vehicular activity, the movement and work of an astronaut outside the Gemini spacecraft.

The predicted problems centered on the physiological response of the astronaut to the workload, the thermal stress, and a suspected low tolerance to fatigue.

In analyzing the results of the Gemini missions with extra-vehicular activity, NASA doctors found that the very systems that were supposed to help the job were creating problems. The forces required to move the space suit were high. The various grips and body-positioning aids attached to the Gemini spacecraft and the Agena target vehicle were inadequate and insufficient in number.

Finally, the fatigue of pre-flight and flight activities may have contributed to the problems of EVA. Astronaut crews all have had trouble sleeping the first night, due to a number of factors, and to follow a sleepless night with the detailed and tiring procedures to get ready for EVA may also have been too much strain on the men.

The portable life-support system, that the astronauts took outside the spacecraft on their working trips, had been designed with the best available information on body-heat and carbon-dioxide removal. But the strains of working in unnatural positions outside the capsule, and forcing every motion against the restraints of the suit, proved too much for the life support system.

But in spite of the troubles, the problems were essentially overcome by good program test analysis and good engineering design, and the medical report on EVA in the Gemini flights concludes that "...there have been no indications that the efficiency of man during extravehicular activities is significantly altered."

About 2,000 hours of weightlessness were logged by Mercury and Gemini astronauts. Basically, the results showed that the anticipated hazards of weightlessness in space flight were less than expected.

There were some bone and blood changes, attributed to the longer-term exposures of the Gemini flights, but no abnormal psychological reactions. Although none of the astronauts reported any problems with vertigo or disorientation, several of the pilots became sea-sick from the motion of the spacecraft on the water after landing.

The classical hazards of space flight — micrometeoroid hits, radiation damage, tolerance to accelerations and decelerations, and disturbances in the normal day-night cycle — appeared to remain confined to the pages of early science-fiction. There were no micrometeoroid hits.

Accelerations and decelerations were tolerated by the crews with no ill effects. And even though their "days" and "nights" were only 45 minutes long, there seemed to be no ill effect from that phenomenon either.

The Gemini medical report stated that the space environment has been much better than predicted. But it added that man has been far more capable in the environment of space than had been predicted.

The extended periods of weightlessness during the Gemini program emphasized a point which had first been observed during the short-duration Mercury operations. The cardiovascular system — the heart and all the fluid ducting in the body — adapted to weightlessness, but did not re-adapt quickly to the strain of reentry.

The first experimental approach to conditioning the cardiovascular system for reentry was the use of thigh cuffs, with pressure alternately two minutes on and four minutes off. This was less than completely satisfactory, so the plans for future long-duration flights are to use whole body exercise and an elastic garment over the lower part of the body.

In the Apollo program, the monitoring of the astronauts' medical status will be chiefly operational in nature. NASA anticipates that standard thermistor thermometers will be used to take body temperature, and that a stethoscope will suffice for measurement of heart sounds. Blood pressure tests will utilize the standard cuff. Electrocardiograms will be taken on selected crew members and radioed to Earth.

But there are still questions which can only be resolved by long-term flights in space. The negative pressure system, for example, should be used. But how much, and how often, and when should it be used?

Astronauts have shown weight losses during space flight, based on pre- and post-flight measurements of body weight.

Measuring body weight periodically and routinely in extended space flight could provide some interesting medical data, NASA doctors believe, but how do you measure body weight in the weightless condition? A joint development program between NASA and the Air Force is working on a mass-measuring system for weightless flights, in hopes of solving this problem.

Exercise seems mandatory to prevent deconditioning of the astronauts during sustained space flight. Isometrics keep up the muscle tone, but they do the cardiovascular system no good because there is no strain on that system. Is there some way to exercise the heart and blood vessels by subjecting them to the simulated strain of physical activity? That subject is under continuing study by NASA medical specialists.

But systematic experimental approach to the medical aspects of long-duration space flight will have to wait beyond Apollo. The Apollo Applications Program Orbital Workshop, planned for future applications of space technology, includes space medicine experiments and facilities in the lists of planned items.

One concern of medical monitors in the space program had been that they were working with healthy specimens, and the fact that there had been little past medical concern with healthy people. As one result, ground-based programs were established to collect normal baseline data, which could be used for comparison with the measured performance of the astronauts during space flight.

There have been some additional indirect benefits of the space medicine program which will, in time, have considerable bearing on the medical problems of a broad segment of the population. Because there were so few astronauts, new sampling techniques had to be developed for projecting their performance, and the performance of future astronauts to come into the program. These new sampling techniques are based on a very small cross-section of subjects, and the use of engineering and computer techniques to extrapolate the measured behavior of the few to the probable behavior of many.

Medical diagnostic techniques have benefited from the manned space flight program. New kinds of sensors, made to be more accurate and more responsive to minor changes in the body, had to be developed. Selected medical data were experimentally analyzed by computer techniques. That combination of new sensors and new analysis techniques promises to benefit all of medicine.

Results That Count

America's first manned space flight was a 15-minute suborbital journey made by Astronaut Alan B. Shepard, Jr., in Freedom 7. This Project Mercury shot, launched May 5, 1961, climaxed the years of work that had preceded the successful flight, and marked the beginning of this country's manned ventures into the space environment.

Two months later, Astronaut Virgil I. Grissom repeated the general pattern of Shepard's flight on the second sub-orbital launch, planned to check the functions of the spacecraft and to evaluate its operation.

Two successes in a row led directly to the first American orbital space flight, made by Astronaut John H. Glenn, Jr., in February 1962. Glenn's Friendship 7 spacecraft orbited the Earth three times in a flight that lasted nearly five hours.

Three months later, Astronaut M. Scott Carpenter flew the same kind of a flight, with a triple orbit of Earth in his Aurora 7 spacecraft.

Five months later, Astronaut Walter M. Schirra, Jr., doubled the orbital flight time of his two predecessors in a six-orbit trip around Earth and a duration of more than nine hours in space. Slowly the experience was building, and slowly the data were being obtained for evaluating the capabilities of man in space.

It was left to Astronaut L. Gordon Cooper, Jr., to make the final flight and to meet the final objective of the Mercury project. Cooper spent more than a day in space, completing 22 orbits of Earth in more than 34 hours.

These had been the first steps — a slow and methodical progression which increased the times in orbit and the amounts of data returned from the flights. The duplicating flights were planned and made to assure that more than luck or coincidence was involved.

It was almost two years — in March 1965 — before the first Gemini spacecraft was launched, carrying Astronauts Grissom and John W. Young into a three-orbit trip in this country's first two-man space flight. This proving flight of the Gemini systems was followed by the epochal 62-orbit flight by Astronauts James A. McDivitt and Edward H. White, II, with its first "walk in space" by White and the first extensive maneuvering of the Gemini spacecraft by its pilot.

In late August 1965, Astronauts Cooper and Charles Conrad, Jr., set another mark with an eight-day stay in space, the first tests of man's capacity for sustained functioning in the space environment.

The closing days of 1965 saw another remarkable achievement of the Gemini program: The world's first successful rendezvous in space, performed by Walter M. Schirra, Jr. and Thomas P. Stafford in Gemini VI–A, in conjunction with Frank Borman and James A. Lovell, Jr., in Gemini VII, who went on to set the world's duration record for manned orbital flight. Borman and Lovell were launched December 4. Schirra and Stafford took off on December 15, completed the approach and rendezvous procedures, and landed the following day after 16 orbits of the Earth. Borman and Lovell remained aloft for another two days, and were recovered December 18.

The first docking of two vehicles in space was accomplished in March 1966 by Astronauts Neil A. Armstrong and David R. Scott, whose Gemini VIII was piloted to a rendezvous and docking with an a target vehicle.

Three months later, Astronauts Stafford and Eugene A. Cernan made three rendezvous with a target vehicle, and Astronaut Cernan spent more than two hours outside the spacecraft in extra-vehicular activity.

A similar three-day mission was performed in Gemini X by Astronauts Young and Michael Collins, who set a new altitude record of 475 miles during their 43 orbits of the Earth. Astronaut Collins transferred by EVA to another vehicle, and retrieved a micrometeorite experiment.

A third three-day mission, completed by Astronauts Conrad and Richard F. Gordon, Jr., made the first flight of tethered space vehicles, and reached the highest point of manned space flight in an apogee of 853 miles.

It was left to Astronauts Lovell and Edwin E. Aldrin, Jr. to complete the Gemini project with 59 orbits of the Earth in mid-November 1966. During their flight, Astronaut Lovell walked and worked outside of the spacecraft for more than 5½ hours. The flight also demonstrated rendezvous and docking, feasibility of station keeping with a tethered vehicle system, and automatic reentry capability.

What has the manned space flight program proved so far? To answer this question would take volumes, because there were two kinds of results from those flights, and enormous amounts of data of all kinds.

The first kind were the gross data, verifying that man could live in space provided he was suitably protected; that he could be recovered safely; that he could rendezvous and dock his spacecraft with others; that he could work outside the spacecraft in the hostile environment of space.

②

The second kind were the refined data, the thousands of little things learned during each flight that made the next one better, or more productive, or safer. There were miles of recorded medical data to analyze. Hundreds of photographs depicted the Earth in a way that could never otherwise be shown to more of the people alive today. There were dozens of observations made by individual astronauts, from Glenn's famous "space fireflies" to Cooper's fantastic visual detection of small objects on the Earth.

There were many engineering observations of the best ways to rendezvous, or to work in space, or to position a handhold. Improvements in the pressure suits resulted from successive flights.

Behind these direct results of the space flights, there is the availability of new technologies that might not have developed without them. Metalworking techniques, new to aerospace, had to be developed; they now serve many needs of defense and commercial air transportation.

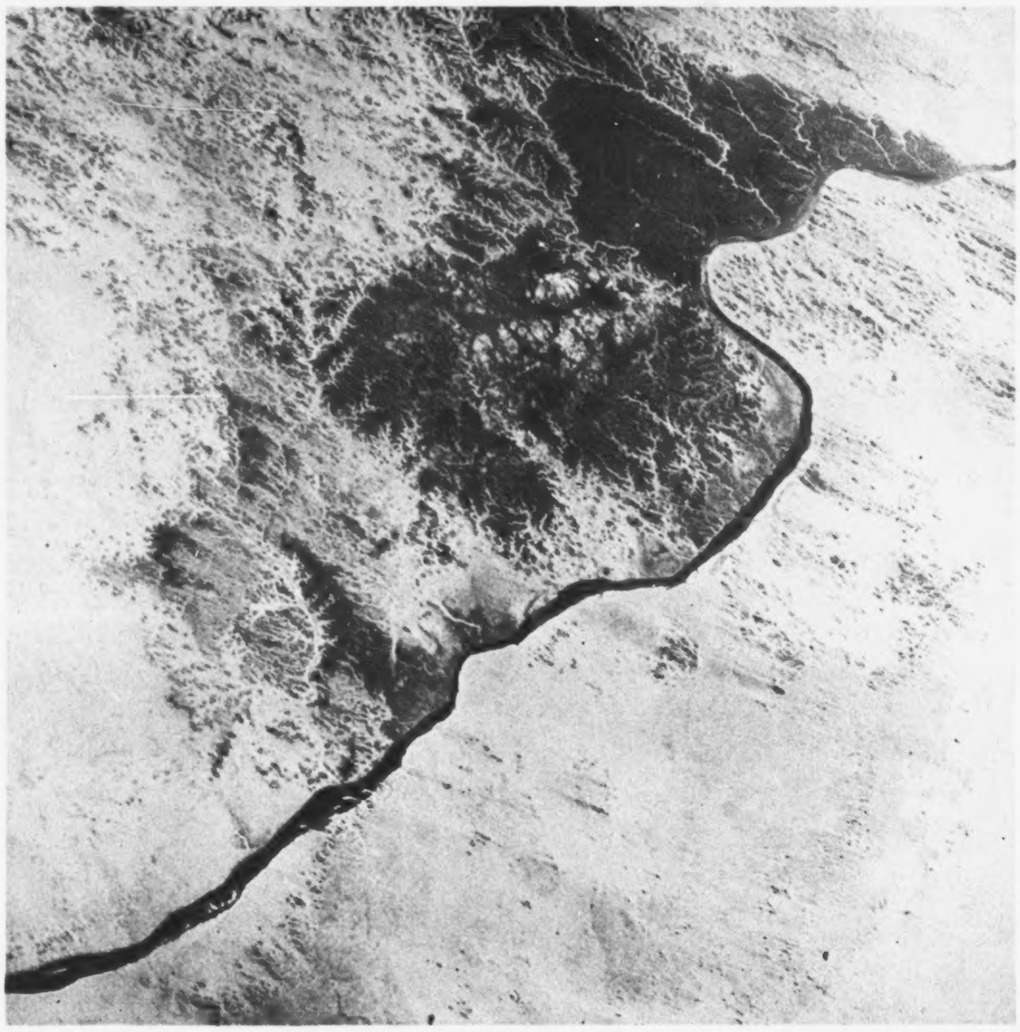
Reliability as a concept and an engineering discipline became newly important, and the techniques developed during the long work of man-rating the systems are still paying off in aerospace applications.

Finally, there were intangible values. The morale of the United States rose and fell. It soared with the exultant spirits of Shepard and Grissom in the first sub-orbital flights, and with Glenn's first orbit of the Earth. It fell with failures.

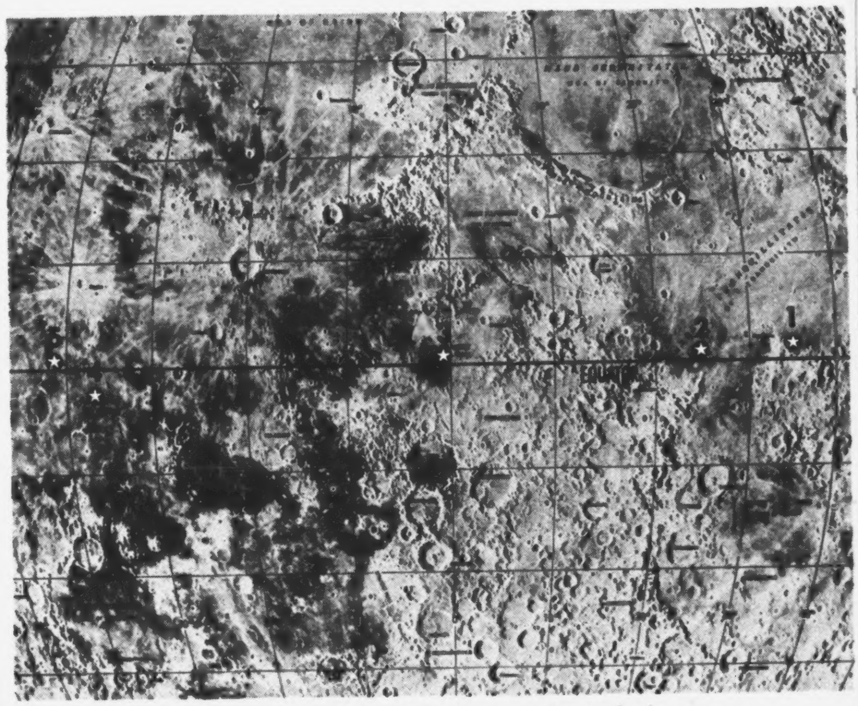
The crowds cheered Carpenter, gave Schirra a parade, roared congratulatioins at Cooper.

In later days, they watched television programs spellbound as the rendezvous pictures were shown and as Astronaut White moved out of the Gemini into space.

18 *A view from Gemini IV of the Nile Valley in southern Egypt. Gemini IV was launched June 3, 1965 and achieved 62 revolutions. The flight lasted 97 hours and 56 minutes.*



19 *A view from Gemini XI of Ethiopia and Somali in northeast Africa showing the Red Sea and the Gulf of Aden.*



20 *Five suitable landing sites have been selected along the Moon's equator. The selections were made after a detailed study of photographs from Lunar Orbiters.*

Still later, they wept at the deaths of Grissom, White and Chaffee, in a ground test of an Apollo spacecraft.

They shared vicariously the triumphs and the difficulties of the manned space program, able to watch them because one of the first decisions had been to make the program open. It was consistent with the concept of a free society, it was argued then, and it was important to keep the world informed of the peaceful nature of the space exploration program which the United States had undertaken.

"We set sail on this new sea because there is new knowledge to be gained," said President Kennedy on September 12, 1962, "and new rights to be won, and they must be won and used for the progress of all people. For space science, like nuclear science and all technology, has no conscience of its own.

"Whether it will become a force for good or ill depends on man, and only if the United States occupies a position of pre-eminence can we help decide whether this new ocean will be a sea of peace or a new, terrifying theater of war."

Epilogue

He packs the surface specimens, the rocks and chunks of rubble, and heads back toward the lunar module. He climbs the ladder and enters.

The lunar module lifts off the surface of the Moon, rising on its thrusting rocket above the descent stage now dwindling from view on the retreating moonscape. The astronauts ride while the guidance system performs the complex calculations and gives the commands that will link the flight path of the lunar module with the orbit of the command and service module above.

Rendezvous and docking follow. The two astronauts take their scientific samples into the command module, joining the third crewman. The lunar module is cast off in lunar orbit.

The service module engine comes to life, thrusting itself and the joined command module out of lunar orbit into a trans-Earth trajectory.

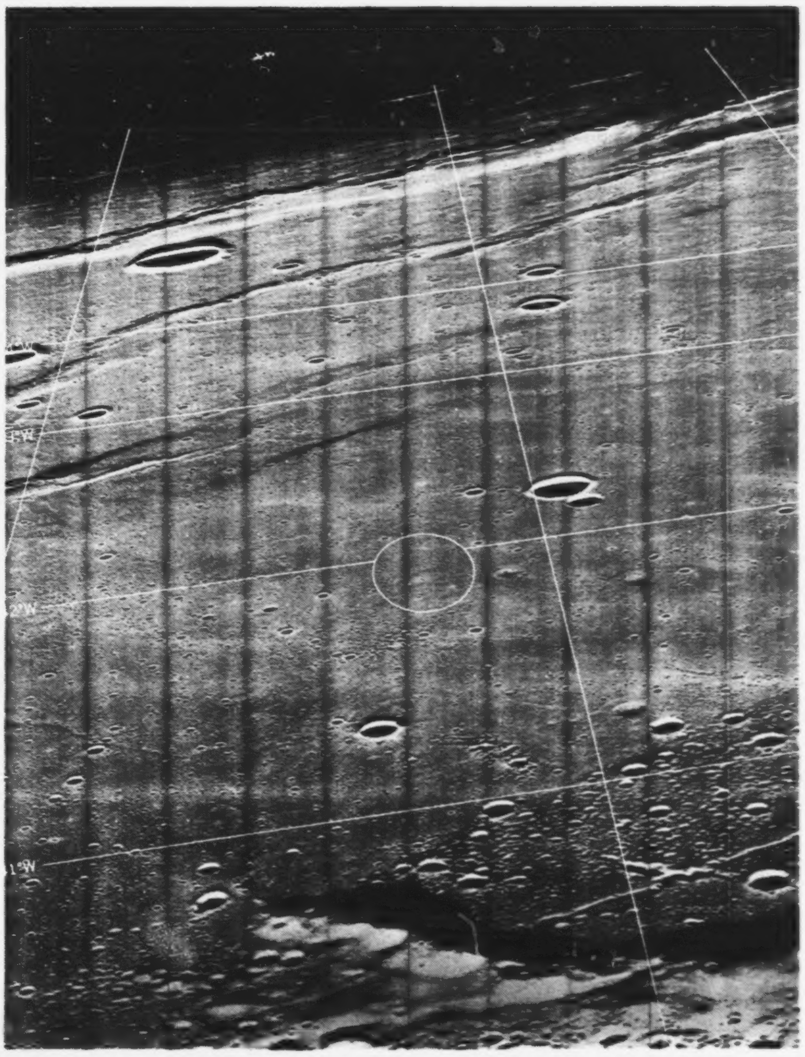
Time passes; three days and some hours, perhaps more. After the initial excitement wears off, the fatigue of the trip and the routine of the long space voyage home set in.

Finally the blue Pacific Ocean shows clearly in the windows. The service module is jettisoned. Reentry begins; the heat shield trails its green halo of plasma and fire. Parachutes deploy at high altitude to increase the drag, and the second trio of chutes opens at 10,000 feet to lower the command module into the ocean off Hawaii.

Eight days ago it had lifted off the pad at Cape Kennedy, in a searing, roaring blast of thrust from the engines of the mammoth Saturn V launcher.

Now it bobs in the water, and the crew waits for the recovery forces to arrive while they secure the spacecraft and themselves after the epochal trip.

To the traditional seven seas of the world-spanning sailor, these astronauts now have added an eighth: The new ocean of space.



21 *This photograph, taken by Lunar Orbiter III on February 21, 1967, shows one of the man landing sites selected by NASA for the Apollo Mission. This is site No. 5 which is located in the Ocean of Storms at 41°40′ West longitude and 1°40′ North latitude on the lunar surface.*

HIGHLIGHTS OF MANNED SPACE FLIGHTS

	Date	Flight Time (Hrs: Min: Sec:)	Revolutions	Spacecraft Name	Remarks
Project Mercury					
Alan B. Shepard, Jr.	5/5/61	00:15:22	Sub-orbital	Freedom 7	America's first manned space flight.
Virgil I. Grissom	7/21/61	00:15:37	Sub-orbital	Liberty Bell 7	Evaluated spacecraft functions.
John H. Glenn, Jr.	2/20/62	04:55:23	3	Friendship 7	America's first manned orbital space flight.
M. Scott Carpenter	5/24/62	04:56:05	3	Aurora 7	Initiated research experiments to further future space efforts.
Walter M. Schirra, Jr.	10/3/62	09:13:11	6	Sigma 7	Developed techniques and procedures applicable to extended time in space.
L. Gordon Cooper, Jr.	5/15–16/63	34:19:49	22	Faith 7	Met the final objective of the Mercury program—spending one day in space.
Project Gemini					
Virgil I. Grissom John W. Young	3/23/65	04:52:31	3	Gemini–III	America's first two-man space flight.
James A. McDivitt Edward H. White, II	6/3–7/65	97:56:12	62	Gemini–IV	First "walk in space" by an American astronaut—by Edward H. White. First extensive maneuver of spacecraft by pilot.
L. Gordon Cooper, Jr. Charles Conrad, Jr.	8/21–29/65	190:55:14	120	Gemini–V	Eight day flight proved man's capacity for sustained functioning in space environment.
Frank Borman James A. Lovell, Jr.	12/4–18/65	330:35:01	206	Gemini–VII	World's longest manned orbital flight.
Walter M. Schirra, Jr. Thomas P. Stafford	12/15–16/65	25:51:24	16	Gemini–VI–A	World's first successful space rendezvous.
Neil A. Armstrong David R. Scott	3/16–17/66	10:41:26	6.5	Gemini–VIII	First docking of two vehicles in space.
Thomas P. Stafford Eugene A. Cernan	6/3–6/66	72:20:50	45	Gemini–IX–A	Three rendezvous of a spacecraft and a target vehicle. Extravehicular exercise—2 hours 7 minutes—by Eugene A. Cernan.
John W. Young Michael Collins	7/18–21/66	70:46:39	43	Gemini–X	First use of target vehicle as source of propellant power after docking. New altitude record—475 miles.
Charles Conrad, Jr. Richard F. Gordon, Jr.	9/12–15/66	71:17:08	44	Gemini–XI	First rendezvous and docking in initial orbit. First multiple docking in space. First formation flight of two space vehicles joined by a tether. Highest manned orbit—apogee about 853 miles. Extravehicular activity lasting 44 minutes by Richard F. Gordon.
James A. Lovell, Jr. Edwin E. Aldrin, Jr.	11/11–15/66	94:34:31	59	Gemini–XII	Astronaut Edwin E. Aldrin walked and worked outside of orbiting spacecraft for more than 5½ hours—a record proving that a properly equipped and prepared man can function effectively outside of his space vehicle. First photograph of a solar eclipse from space.

APOLLO FLIGHT CREWS

(as announced August 8, 1968)

First Manned Flight (Saturn IB)

Prime Crew	Command Pilot, Walter M. Schirra, Jr. Senior Pilot, Donn F. Eisele Pilot, Walter Cunningham
Backup Crew	Command Pilot, Thomas P. Stafford Senior Pilot, John W. Young Pilot, Eugene A. Cernan
Astronaut Support Team	John L. Swigert, Jr. Ronald E. Evans William R. Pogue

Second Manned Flight (Saturn V)

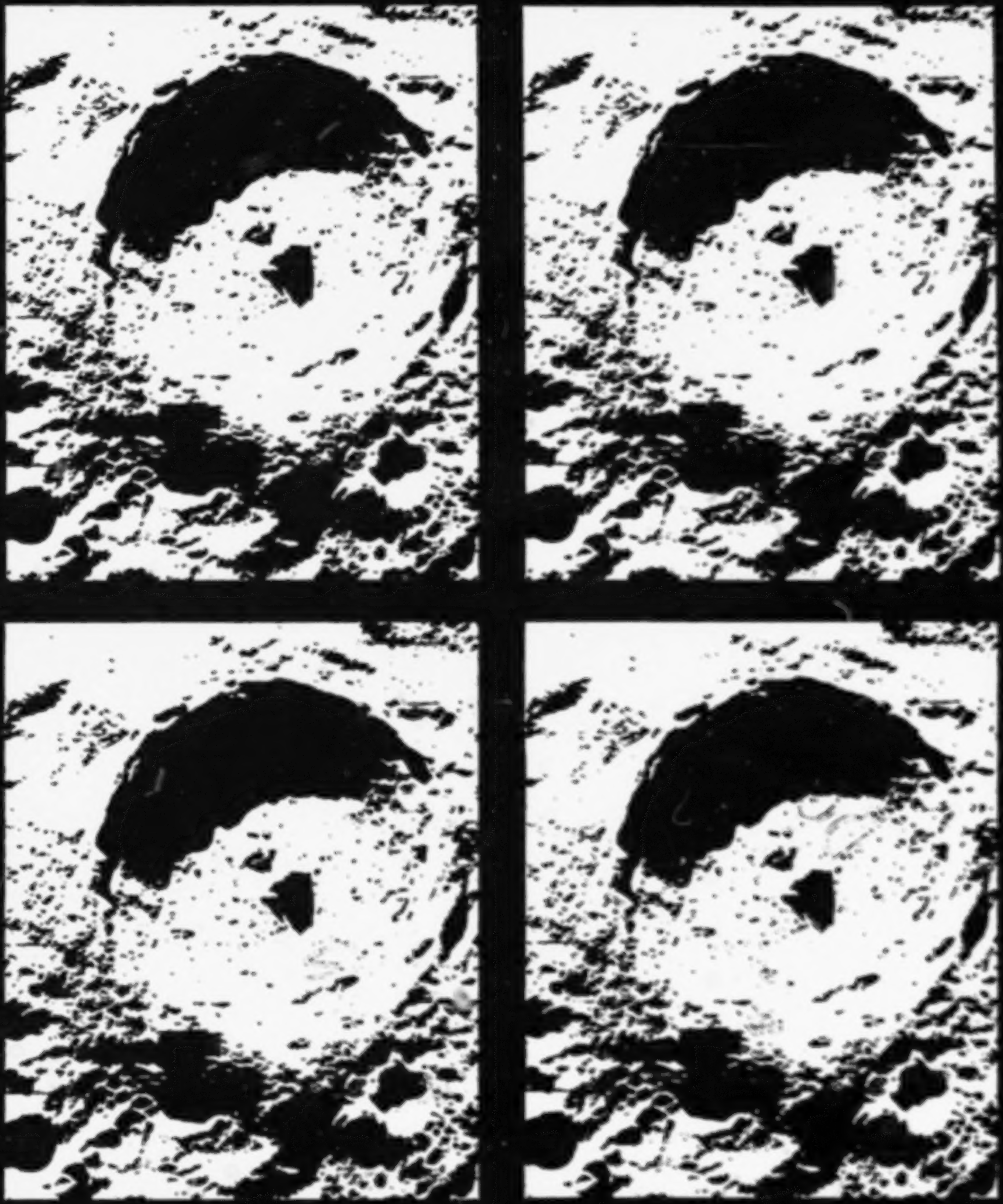
Prime Crew	Commander, James A. McDivitt Command Module Pilot, David R. Scott Lunar Module Pilot, Russell L. Schweickart
Backup Crew	Commander, Charles Conrad, Jr. CM Pilot, Richard F. Gordon LM Pilot, Alan L. Bean
Astronaut Support Team	Edgar D. Mitchell Jack R. Lousma Alfred M. Worden

Third Manned Flight (Saturn V)

Prime Crew	Commander, Frank Borman CM Pilot, James A. Lovell, Jr. LM Pilot, William A. Anders
Backup Crew	Commander, Neil A. Armstrong CM Pilot, Edwin E. Aldrin, Jr. LM Pilot, Fred W. Haise, Jr.
Astronaut Support Team	Thomas F. Mattingly, II Gerald P. Carr Vance D. Brand

America In Space | The First Decade

Exploring the Moon and Planets



National Aeronautics and Space Administration

America
In
Space:
The
First
Decade

This is one of a series of booklets published on the occasion of the 10th Anniversary of the National Aeronautics and Space Administration.
These publications are not intended to be comprehensive history, nor do they deal with all the facets of NASA's aeronautical and space activities. Rather they are overviews of some important activities, programs and events written for the layman in terms of the several science disciplines.

Each of these subjects is treated in more depth in other NASA publications and in scientific journals.

1 October 1968

Titles in this series include:

I Space Physics and Astronomy
II Exploring the Moon and Planets
III Putting Satellites to Work
IV NASA Spacecraft
V Spacecraft Tracking
VI Linking Man and Spacecraft
VII Man in Space

Others are in preparation. Topics include:

Propulsion
Spacecraft Power
Space Life Sciences
Aeronautics
Space Age By-products
Materials

EXPLORING
THE
MOON
AND
PLANETS

by William R. Corliss

National Aeronautics and Space Administration, Washington, D.C., 20546

Introduction

Ten years ago when the National Aeronautics and Space Administration was brought into being to explore space, it began immediately to give thought to exploring the Moon and the planets. From its beginning NASA has been interested in the scientific studies of these bodies. Since 1961 it has had the added responsibility of securing information concerning the Moon that would be needed for a manned expedition to the Moon. In the ten years of NASA's existence our knowledge of the Moon has increased immeasurably; we know the far side as well as the front. We have seen a portion of the surface of Mars from nearby. We have made measurements close to Venus. "Exploring the Moon and Planets" presents the findings made in the first ten years of the existence of NASA. It is one of the avenues selected by the Agency to disseminate the knowledge that it has gained in its program in keeping with its responsibilities.

John E. Naugle
Associate Administrator for
Space Science and Applications

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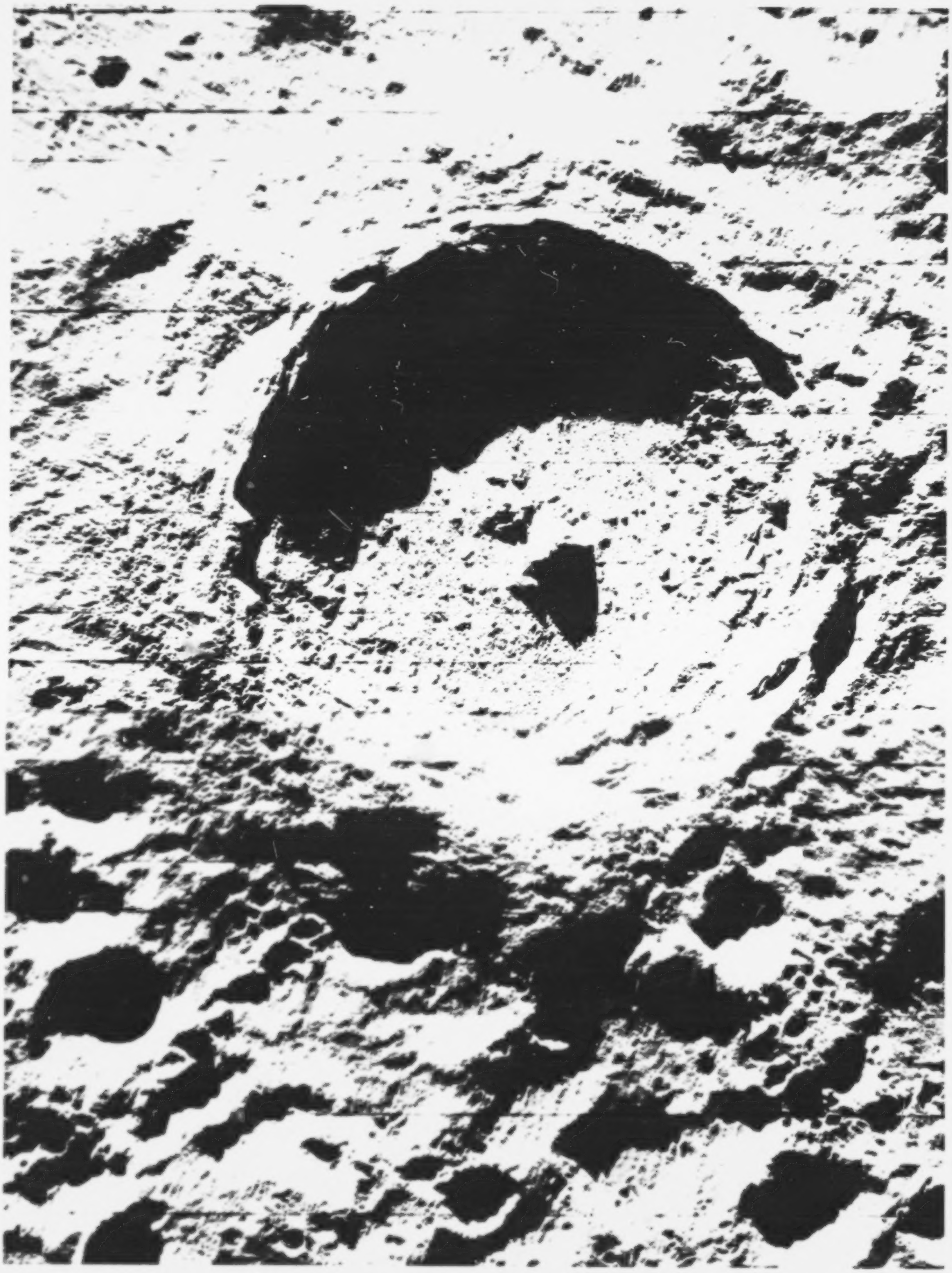


Exploring the Moon and Planets

An Earth Dweller's View

The positions of the planets at your birth fix your destiny—so said the ancient astrologers. Many people still believe this to be true. Others know for certain that sleeping in the moonlight courts lunacy.

Not content with superstitious speculations, scientists have watched and measured the motions of the Moon and planets for thousands of years. First, they used the naked eye; then, the telescope; and, more recently, spectroscopes and other modern instruments. Only a decade or so ago, astronomers were well satisfied with the apparent order they had found in the solar system. To be sure, the Earth's Moon was indecently large to be a satellite, and the axis of Uranus pointed the wrong way. But, by and large, only a few problems remained to be ironed out before the origin, evolution, and future of the Sun's little group of planets could be described with assurance.

Space probes and radar astronomy have changed all that. We know now that Mercury rotates with unconscionable rapidity; while its cloud-shrouded neighbor, Venus, turns hardly at all and the wrong way at that. Mars, which seemed an older version of Earth to scientists of 1900, has been found pock-marked with great craters. Frozen Jupiter has a magnetic field many times that of Earth and radiation belts to match.

In just a decade, our comfortable view of the solar system has been shaken to its foundations. Solar system astronomy is in ferment.

The Moon Through the Telescope

The first thing man wanted to know about the Moon was where it was going to be and when. Eclipses, especially, were events of great religious concern. Even primitive man was able to discover a great deal of order in the Moon's motions. Visualize the precision of the huge circles of stone markers at Stonehenge. How many centuries did Stonehenge's builders watch the Moon and mark its progress before they discovered its lengthy eclipse cycle?

Today, we are more interested in knowing where the Moon came from and what it's made of. Surprisingly, just by watching it through the telescope we can

1 *Some lunar local hot spots. Dots indicate hot spots; shaded areas, widespread thermal anomalies.*

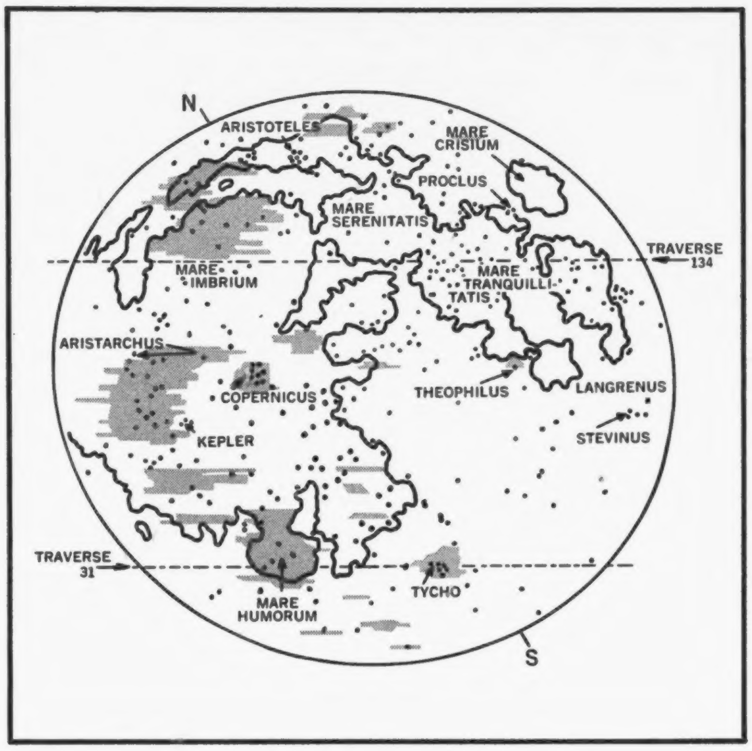
narrow down the range of possible answers. First, the Moon is big as natural satellites go—the Earth being only 80 times heavier. It is also quite close—about a quarter million miles away. Astronomers, in fact, tend to think of the Earth-Moon corporation as a double-planet. The two spheres revolve like a lop-sided dumbbell about their common center of mass, located some 3000 miles from the Earth's center toward the Moon. No other solar system planet can claim such an out-sized moon.

The Moon is so big and so close that its gravitation pulls our atmosphere, our oceans, and even the Earth's rocky mantle out of shape, although only slightly in the latter instance. The energy absorbed by the friction of these tides comes ultimately from the motion of the Earth and Moon. As a result, the Earth's day increases about 33 seconds per century and the Moon is slowing down in its orbit. As the Moon slows down, it slowly recedes from the Earth. Here is where we get some insight into the past history of the Earth-Moon system. Working the tidal friction theory backwards, scientists such as Gordon J. F. MacDonald arrive at the conclusion that the Moon would have receded to its present distance in 1.3 billion years. However, the Earth's age is apparently some 4.5 billion years, inferring that the Earth-Moon partnership may not have been created when the Earth was born.

Well, then, whence the Moon? Perhaps the Moon was once an asteroid that wandered in from the belt between Mars and Jupiter and was somehow gravitationally snared by the Earth. (One can imagine the terrestrial geologic upheavals accompanying such a union.) Or, as George H. Darwin, Charles' son, calculated around 1880: The Earth might have spun off a glob of Moon stuff eons ago when it was rotating much faster on its axis. Some believe that the Pacific Ocean basin is the scar left by this planetary fission.

Another intriguing observation: knowing the Earth's mass and the Moon's distance, astronomers can infer the Moon's mass and measure its diameter through the telescope. The average density of the Moon is only around 3.4, much less than the Earth's average of 5.5; yet it is close to the density of the lighter rock forming the Earth's crust. The advantage of the lunar probe is now obvious; it can analyze directly the composition of the surface of the Moon and see if it resembles that of the crust of the Earth.

The most obvious feature of the Moon through the telescope—even good binoculars—is its cratered surface. For the first half of this century, just about everyone believed that lunar craters were meteor craters. The Moon was supposed to be a cold, dead world "where nothing ever happened," so, the craters could not be of volcanic origin. Besides, the Earth, too, is pock-marked by huge craters. Photos



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from aircraft (and more lately satellites) have revealed many well-weathered craters right here on Earth, particularly in Canada and the Carolinas. It could be that both sets of craters were born during and after the Moon's birth pangs or its cataclysmic capture.

But is the Moon really dead? On the night of April 18, 1787, the great German-English astronomer William Herschel saw a red area near the crater Aristarchus glowing like "slowly burning charcoal thinly covered with ashes." Over the centuries, many Moon watchers have seen flashes of light and glowing red spots. Some old craters even seem to have disappeared. Despite the imperious pronouncement that the Moon was dead, over 400 "transient lunar events" have been recorded over the past five centuries. Apparently, the Moon's pulse still beats—though perhaps weakly.

Astronomers can also watch the Moon through our atmosphere's infrared window.* During the lunar eclipse of March 13, 1960, for example, Richard W. Shorthill and his associates noticed that the infrared temperatures of the floors of some of the lunar craters did not fall as rapidly as the rest of the shadowed surface. More recently, infrared maps of the Moon have revealed many hot spots. The erratic visual red spots seen by Herschel and many others since may be lava flows or some other surface manifestation of lunar volcanic activity. Nonthermal explanations also exist; areas of the Moon might glow when stimulated by Sunlight—or possibly the solar wind.

The telescope has obviously been a powerful tool in learning about the Moon. But there is a limit to what we can do with Earth-based tools. A well-equipped scientist-astronaut on the spot could best find out what is really transpiring on the Moon. First, though, there is an active lunar experiment we can carry out from Earth.

Radar Astronomy Of the Moon

The only kind of experiment we can perform on the Moon across a quarter million miles poses its questions electromagnetically. To do this, we aim a radar transmitter at the Moon, send out short pulses of radio waves, and wait for the echoes to arrive some 2½ seconds later. In radar parlance, the echo gives us the Moon's radar signature, which can be most revealing to the radar graphologist. For example, a smeared echo that is strong in the beginning and then trails off in a few microseconds reveals that the radar signal is being reflected from a rough

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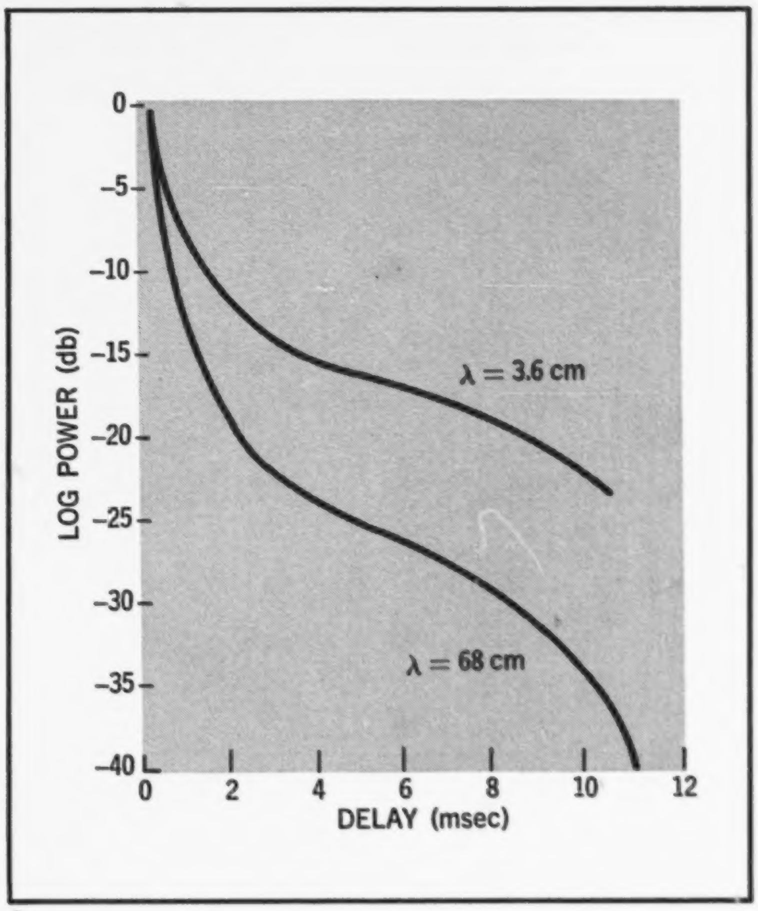
** Our atmosphere blocks out most radiation from space; the "windows" are open to visible, some infrared and most radio frequencies.*

2 Radar echoes at 3.6 cm from the Moon are not as sharp as they are at 68 cm. The higher echo tail at 3.6 cm indicates that rough terrain around the aiming point is also contributing to the signal.



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spherical surface. A perfectly smooth Moon would yield a sharp echo with no trailing edge. This is equivalent to shining a flashlight on a highly polished ball (say, a Christmas tree ornament) and seeing only a bright reflection from the center of the ball.

The first lunar radar echos were obtained just after World War II; but it was not until 1960 that radars were powerful enough to make a study of surface detail. When the Moon is illuminated with radar waves longer than 10 centimeters (4 inches) its surface appears rather smooth. 3.6 centimeter waves, however, show strong echoes from rough spots on the lunar surface. Lunar roughness, then, is small scale roughness—something like sand and gravel rather than boulder fields. However, because the echoes at long wave-lengths are not perfectly crisp and sharp, we know that some larger rubble also exists. Larger features, such as the lunar mountains, can be mapped by timing the echoes in the same way that aircraft radars see the terrain below them.

Radar makes use of another technique. When a radar wave hits the lunar surface, the strength of the echo depends upon a factor called the dielectric constant of the surface. Metals are superb reflectors; solid rock, not so good. By measuring the power in the returning echo, radar astronomers find that the Moon's surface has a dielectric constant only about half that of solid rock. In fact, lunar echoes resemble those from dry, sandy soil here on the Earth. Thus, even before the Surveyor space probes landed on the Moon, radar probing from Earth had provided a surprising amount of information about the lunar surface.

Some Hard Landings And Near Misses

The next step in the exploration of the Moon, beyond the telescope and the radar, is to go there; first by proxy with an unmanned instrument carrier and, soon, with man himself. Unmanned space probes have led the way; they are simpler, smaller, and the information they send back about the Moon is essential to any manned venture.

Summary of NASA's Lunar And Planetary Programs

Program	Number of Flights	Launch Dates	Target	Type of Mission
Pioneer	5	58–59	Moon	Flyby
Ranger (phase 1)	5	61–62	Moon	Hard landers
Ranger (phase 2)	4	64–65	Moon	Hard landers
Lunar Orbiter	5	66–67	Moon	Orbiters
Surveyor	7	66–68	Moon	Soft landers
Apollo	–	68+	Moon	Manned landers
Mariner II	1	62	Venus	Flyby
Mariner IV	1	64	Mars	Flyby
Mariner V	1	67	Venus	Flyby

In order of marksmanship and technical sophistication required, the feasible space probe missions are: (1) a near miss or flyby; (2) a hard landing or unbraked impact; (3) a swing around the Moon, coming back toward Earth; (4) an orbit around the Moon; and (5) a soft landing. As mission difficulty increases so does the scientific potential of the probe.

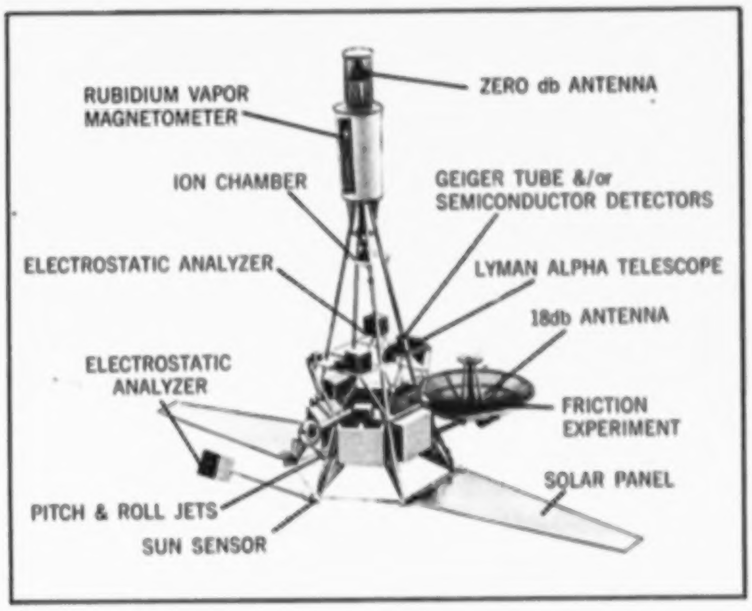
Both the United States and Russia were interested in the Moon early in their space programs. The U.S. Pioneer space probes flew toward the Moon; they were instrumented to explore space between the Earth and Moon (called cislunar space). The only Pioneer instrument that might have provided insight about the Moon itself was a magnetometer. The Pioneer that came closest to the Moon was Pioneer IV (launched March 3, 1959), which passed 37,300 miles from the Moon on its way into orbit about the Sun. Those early Pioneers contributed greatly to our understanding of the Earth's Van Allen Region and the solar wind.

Russia's Luna 1 was launched on January 2, 1959 and passed within 3728 miles of the Moon. Luna 2 scored a direct hit a few months later. A magnetometer on Luna 2 indicated that the Moon possesses a very weak magnetic field. Luna 3 did even better; launched on October 4, 1959, it was temporarily captured by the Moon's gravitational field on October 6, swung around the Moon, and headed back toward Earth, where it went into orbit. While swinging around the Moon, Luna 3 took 40 minutes of pictures on 35-mm film. When the film was automatically developed and its images relayed back to Earth, the world had the first photographs of the Moon's back side, although the pictures did not have high resolution.

The United States undertook its first lunar exploration in the Ranger Program. Originally, the first Ranger spacecraft, the Block I models, were to fly by the Moon, making measurements of micrometeoroids and radiation in the space near the Moon like the Pioneers. Toward the end of the program, Block II Rangers were to drop packages of instruments onto the lunar surface. Rangers I and II, the two Block I spacecraft, were launched in the latter half of 1961. Neither was injected successfully into a Moon-bound trajectory.

3 *Photograph of a Block I Ranger.*

4 *Picture taken by Ranger IX from 258 miles, showing the crater Alphonsus..*



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During 1962, the three Rangers in Block II departed from Earth satisfactorily. But, because of launch vehicle problems, Rangers III and V missed the Moon (only by 450 miles in the case of Ranger V). Ranger IV landed on the back side of the Moon, but its instrument package was destroyed when a timer failed to fire a retrorocket.

Block III was created when President Kennedy declared that landing a man on the moon by 1970 was a national goal. The mission of Rangers VI through IX was to obtain close-up pictures of the Moon's surface during approach to a hard landing in support of the man-on-the-Moon goal.

On January 30, 1964, Ranger VI left the launch pad for the Moon. Everything looked great up to a few seconds before impact on the Moon, but no pictures arrived back at Earth. It was later discovered that the television camera had been accidentally turned on while the probe was ascending through the Earth's atmosphere. Electrical arcing had occurred, damaging the camera. The remainder of the Ranger program was outstandingly successful. Rangers VII, VIII, and IX returned over 17,000 excellent photographs of the lunar surface in 1964 and 1965.

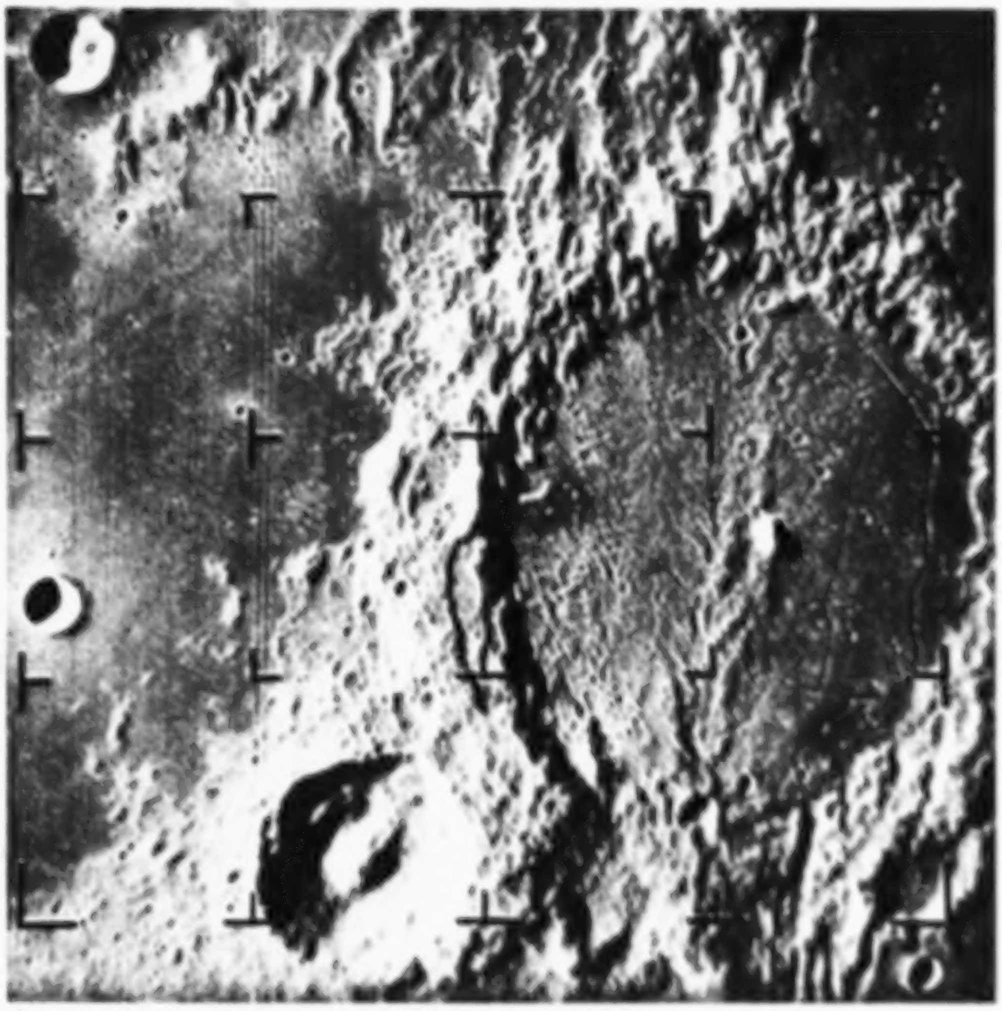
With visual resolution a thousand times those of the best Earth-based telescopes, scientists hoped that the Ranger pictures might settle some of the lunar controversies. Details less than two feet across could be seen. But the photos could not tell what the Moon was made of, nor was obvious volcanic activity seen. What science did gain was a tremendous mass of detailed terrain information, plus a few new perplexities.

In the Ranger pictures, countless craters of all sizes dominate the lunar maria (dark areas) that look so smooth through the telescope. The smaller the crater diameter, the more there are. Most of the craters smaller than 1000 feet in diameter have smoothly rounded rims, giving them a windblown appearance, which is quite contrary to the impression given by the larger, much sharper craters seen through the telescope.

The smaller lunar craters are nonuniformly distributed. Many seem to be secondary craters occupying the bright "rays" we see around large craters through the telescope. Presumably, these swarms of secondary craters are formed by debris or ejecta thrown out from the primary crater when it was formed.

The Ranger photos show few rocks and little rubble. Numerous collapse features, such as crevasses and crater slumpings, were photographed.

Ranger IX obtained some excellent close-ups of the prominent crater Alphonsus (diameter about 50 miles) and its surroundings. Many of the transient lunar events noted by earlier observers had occurred around the crater. Do the Ranger photos sustain the view that internal thermal activity still transpires in and around it? The answer is a fairly definite yes, although Alphonsus seems no different from many other large lunar craters. It boasts a striking central peak standing incongruously in the center of the relatively flat crater floor. Detailed Ranger photos show this peak to be nearly featureless and twice as bright as its surroundings—almost as if it were covered with snow. Snow is manifestly impossible on the cloudless, airless Moon.



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But thermal activity, such as the fumaroles seen at Yellowstone, might produce mineral frosting on Alphonsus' central peak. In addition, eight subcraters on the floor of Alphonsus are surrounded by dark halos and occur squarely on long cracks (rills). The thin blankets of dark material have partially filled the rills, indicating perhaps that debris or ash might have been ejected from the craters due to subterranean activity where the lunar crust was weakened by the crack.

The Rangers also radioed back some photos of systems of wrinkle ridges, where the surface seems to have been compressed horizontally. Wrinkle ridges are generally accepted as evidence of internal activity on the Earth.

Actually, many lunar craters seem to be due to impacts of meteoroids. However, the collision of a large meteoroid might so fracture the Moon's crust that it would set off secondary volcanic activity, causing the observed lava flows and eruptions of ash. It is in this sense that the Ranger photos do not resolve the crater controversy. Craters seem to be both meteoric and volcanic in origin.

The Ranger missions have given us many more facts that will eventually result in better hypotheses. And, of course, the Rangers assured the engineers designing the Apollo manned lunar landing craft that they would be able to find large, smooth areas on the lunar surface for landings.

Surveyor's View

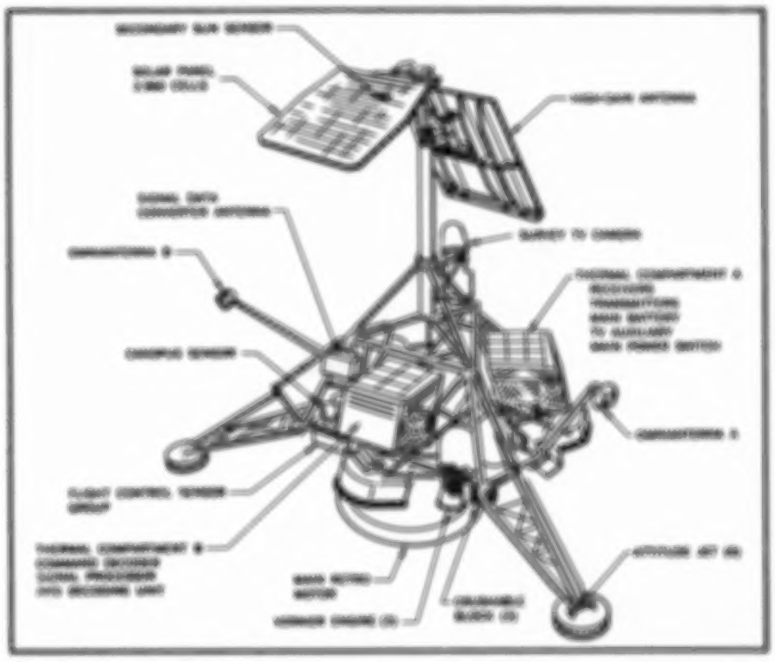
Seeing may be believing here on Earth, but we need something more revealing than photographs to understand the Moon. Just a simple lump of Moon stuff in a terrestrial laboratory would answer many of our questions, but this is still in the future. Today, we must make do with unmanned, unrecallable instrument carriers. Despite these limitations, there is a great deal we can learn over the quarter-million mile radio link between the Earth and a soft-landed lunar instrument package.

The U.S.S.R. tried to develop soft lunar landers in their Luna series. The first try at a soft lunar landing

5 The Surveyor configuration.

6 General terrain seen by Surveyor I. Surveyors that landed in maria viewed similar expanses of flat, rubble-strewn lunar landscape.

7 Surveyor I photo showing footpad sinking into lunar surface.



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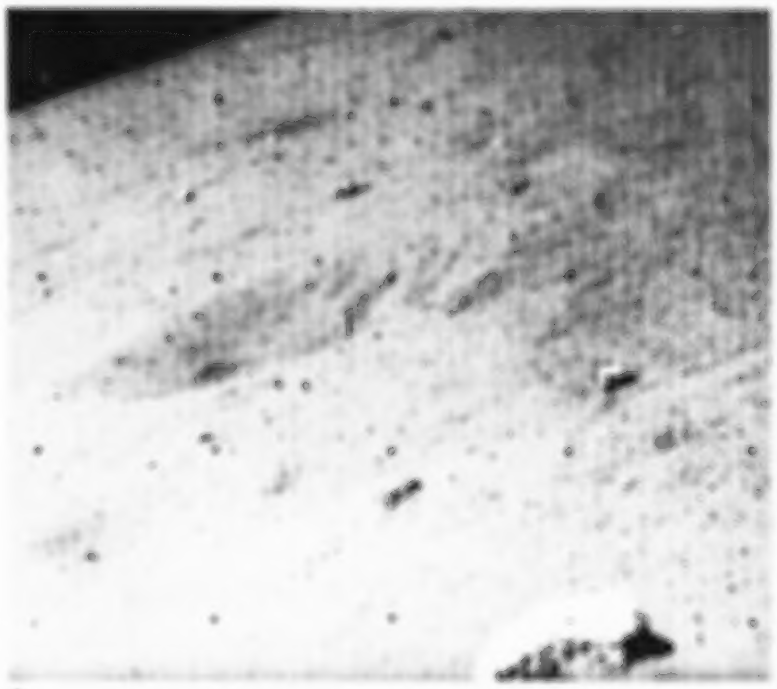
apparently was June 8, 1965, but Luna 6 missed the Moon completely. Later in 1965, two more Lunas (7 and 8) did hit the Moon, but much too hard (the retrorockets failed). Finally, on January 31, 1966, Luna 9 left a launch pad at Tyuratam and 79 hours later crashed on the lunar surface. But first it had ejected a 220-pound spherical capsule that braked itself to a soft landing on the western margin of Oceanus Procellarum. This vehicle then snapped 27 pictures with its single camera in three days.

The first major fact of the Luna 9 flight was that the spacecraft did not drown in a sea of loose Moon dust as some had predicted. The lunar surface apparently could serve as a safe landing platform for men. Luna 9's foundation was evidently not completely secure, because the spacecraft shifted twice while it was taking pictures possibly due to minor crumbling of the surface. The camera viewed an undulating landscape pockmarked with craters of various sizes and littered with fragments of material. Nearby, the lunar surface seemed to be porous, and some scientists immediately suggested that it was vesicular (frothy) lava—that is, a solid but foamy substance. The majority view inclined toward a weakly cohesive collection of fragmented material—something like sand with particles of many sizes.

Originally Surveyor's objectives were primarily scientific in character, but when the Apollo Program began to focus U.S. space efforts in 1961, the mission assumed some of Apollo's engineering tasks. While the Lunar Orbiters surveyed the lunar surface for suitable landing sites, the Surveyors soft-landed to determine the hazards of the lunar surface, particularly the characteristics of the soil, rock, or whatever the surface turned out to be. The first Surveyor left Cape Kennedy for the Moon on May 30, 1966, successfully soft landed, and transmitted over 11,000 fine photographs.

All around Surveyor I stretched a gently rolling surface studded with craters from an inch to a thousand feet in diameter. A sprinkling of fragments, large and small, covered the terrain. The spacecraft's footpads could be seen by the camera, and they had penetrated the surface an inch or so. The top part of the lunar surface, then, was definitely sandy and not solid lava. This was supported by firing a vernier engine to see if it would stir up dust. It did not.

One of the most interesting photos taken by Surveyor I shows a rock about a foot and a half long, with rounded contours and distinct porosity—much like the "bombs" that are sometimes spit out by terrestrial



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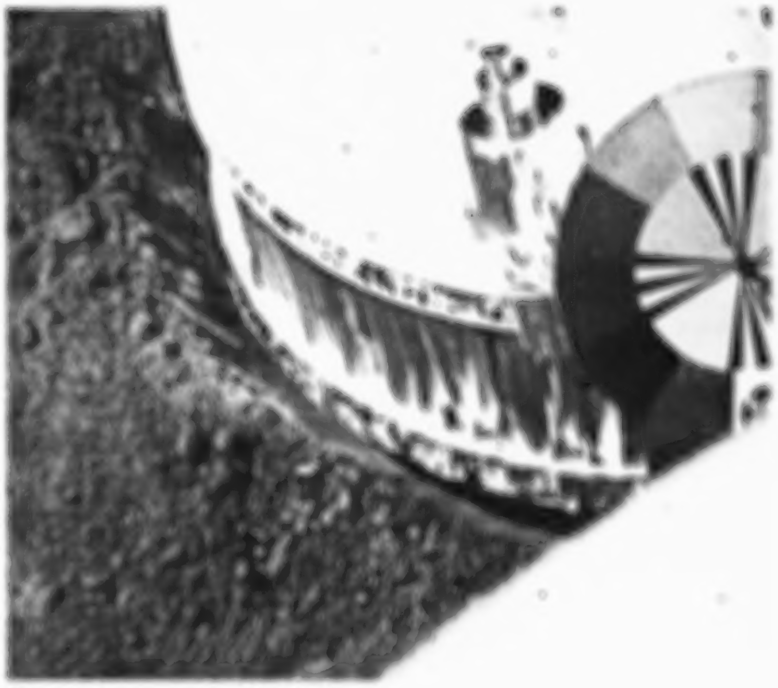

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volcanoes. Lunar geologists feel that it could also be a solidified glob of lunar material that was melted by and tossed there by the impact of a large meteoroid.

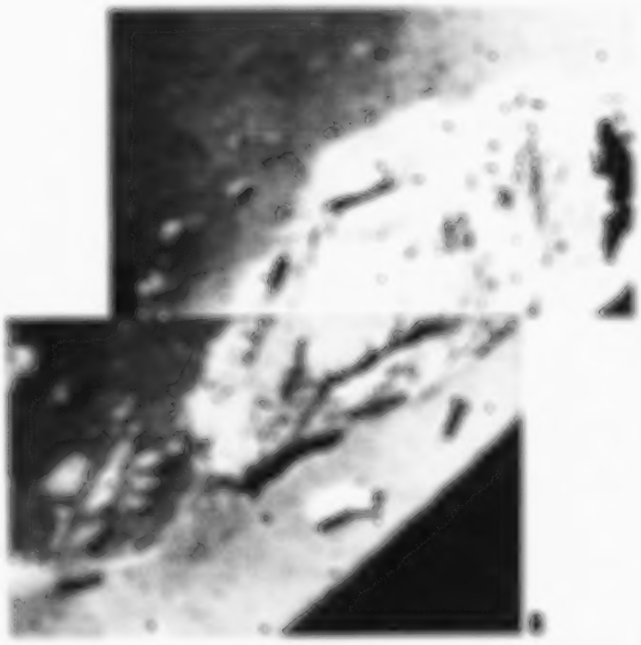
Surveyor II was launched on September 20, 1966, but mid-course difficulties prevented a soft landing, and the Moon had one more crater added to its roster. On December 24, 1966 Luna 13 soft-landed on the Moon's surface. The Russians have reported receiving pictures similar to those of Luna 9, although the overall terrain was much smoother. Luna 13 carried a probe rod to measure the density of the upper layer of lunar material. A Geiger counter measured the amount of gamma rays coming from the soil. Evidently, the soil is slightly less dense than water on the top. The inference is that the Moon's surface has about the strength of terrestrial soil.

On April 20, 1967, Surveyor III bounced to a landing 390 miles from Surveyor I. The unplanned bounces had value, for the lander's camera was able to photograph the "footprint" made by one of its footpads at the next-to-last touchdown. These photos plus data from strain gages attached to the landing gear provided data on surface strength that showed that man could land and walk safely on the Moon.

When the 6315 Surveyor III pictures were studied, they revealed that the spacecraft had landed in a shallow crater 656 feet in diameter. Panorama views of the lunar surface were impossible. Camera problems, including glare caused by the tilt of the spacecraft caused difficulties in obtaining good pictures.

Surveyor III was not as passive as its predecessors. With a remotely controlled mechanical hand (called a surface sampler) it could do something besides look. By digging four trenches and by pressing and hitting the lunar surface, the surface sampler showed the lunar soil to be much like damp sand. The walls of the trenches did not cave in, nor was the soil hard to dig. A piece of rock picked up by the sample was not crushed or broken when subjected to a pressure of 100 pounds per square inch. In other words, the Moon's surface layer was moderately cohesive and the objects that looked like rocks were rocks.

Close study of the bigger rocks scattered about Surveyor III give the impression that they are partially "submerged" in lunar material. There are no craters or depressions around them. Somehow, lunar material tends in time to fill in depressions. Yet, there is no accumulation of material around the rocks



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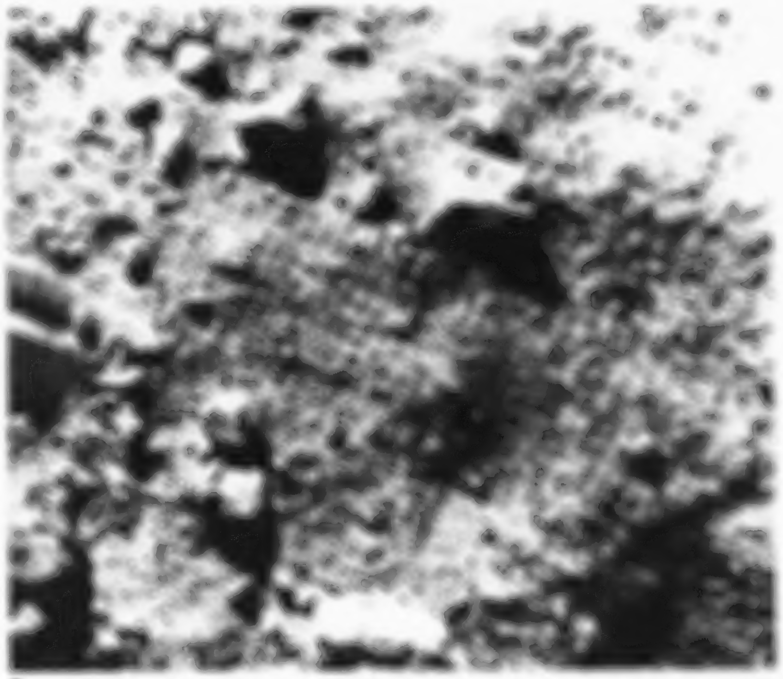
One of the lunar rocks photographed by Surveyor I. Rock may be of volcanic or meteoric origin.



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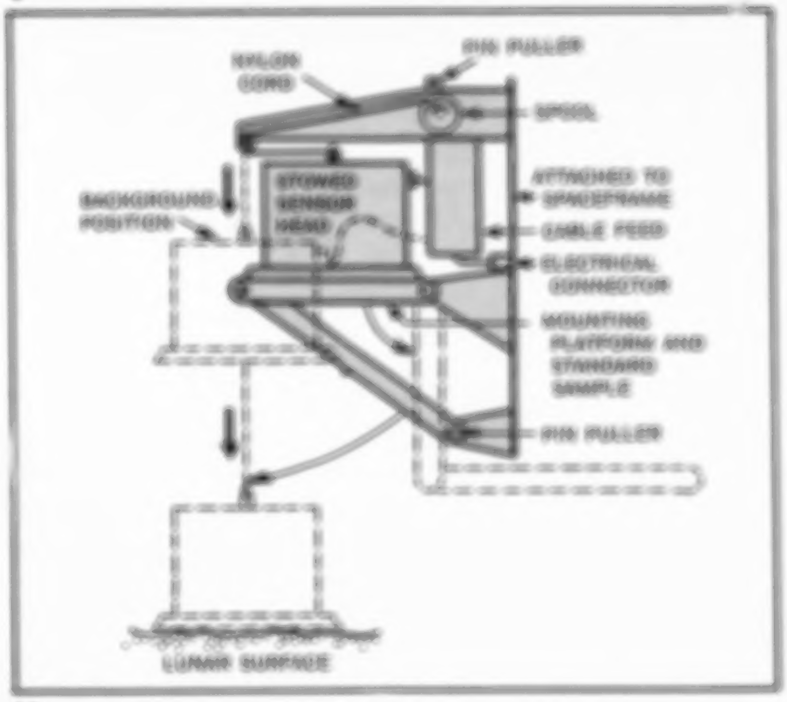
Small area on lunar surface strewn with loose fragments scattered by Surveyor V as it landed in a small lunar crater on September 10, 1967.


NYLON CORD
PIN PULLER
SPOOL
STOWED SENSOR HEAD
BACKGROUND POSITION
ATTACHED TO SPACEFRAME
CABLE FEED
ELECTRICAL CONNECTOR
MOUNTING PLATFORM AND STANDARD SAMPLE
PIN PULLER
LUNAR SURFACE

10

The alpha-scattering experiment on the later Surveyors was lowered to the lunar surface by an escapement mechanism. It provided the first direct measurements of lunar composition.

11 *Mosaic of pictures taken of surface sampler operations around the base of Surveyor VII in January 1968. Excavations were made to determine the nature of the lunar surface.*

as there would be with windblown sand or snow on the Earth. Just what the nature of this gentle lunar "rain" is, no one knows.

Surveyor V, the next successful probe in the series, braked to a soft landing on the Mare Tranquillitatis on September 11, 1967. Although Surveyor V relayed over 18,000 excellent pictures with high scientific content on its first day, and more after two cold, lonely weeks in the lunar night, this spacecraft will be remembered for its alpha-scattering experiment. By shooting alpha particles (doubly ionized helium atoms) into the lunar surface material and measuring the energies of alphas that bounce back and the energies of protons created in nuclear reactions in the lunar material, man made his first chemical analysis of the Moon. Once the spacecraft had landed safely, a signal from the Earth fired two explosive "pin-pullers" that freed the sensor head of the alpha-scattering

11

experiment. In a Rube Goldberg-like sequence, the sensor head swung free in the weak lunar gravitational field and was slowly lowered to the ground by an escapement mechanism. The curium-242 alpha source fired its subatomic bullets into the soil and counters measured the particles that flew back. Data from the counters were flashed back to Earth (1⅓ seconds transit time). Atoms that no number of photos could identify were catalogued. Essentially, the top layer of the lunar mare surface closely resembles terrestrial basalt, the rock underlying all oceans and continents.

A basaltic lunar surface gives scientists confidence that terrestrial geochemical processes also can be applied to the Moon. In other words, since the Earth and Moon may possess similar basaltic outer shells, the Moon may have evolved like the Earth. Although scientists are still wary of Darwin's theory about the Earth giving birth to the Moon, the apparent discovery of basalt-like material on the Moon tends to give this theory a credibility it has not had in decades.

Alpha-Scattering Experiment Analysis of the Lunar Surface at the Site of Surveyor V

ELEMENT	ATOMIC PERCENT*
Carbon	<3
Oxygen	58.0±5
Sodium	<2
Magnesium	3.0±3
Aluminum	6.5±2
Silicon	18.5±3
Atoms with atomic weight between 28 and 65	13.0±3
Iron, cobalt, nickel	>3
Atoms with atomic weight above 65	<0.5

** Excluding hydrogen, helium, and lithium, which cannot be measured with this instrument.*

The success of Surveyor V was followed by that of Surveyor VI, which also settled down to a landing spot on a lunar mare. More basalt-like material was found in the new location.

With many thousands of mare pictures in their hands, two basalt measurements, and safe landing spots for astronauts assured, scientists recommended that the last Surveyor be set down in the rugged lunar highlands. Lunar Orbiter photos had demonstrated dramatic differences between the two types of lunar terrain; i.e., highland craters are fewer and some of them are fresh.

Surveyor VII landed just north of the crater Tycho in the lunar highlands on January 9, 1968. It touched down only 1.2 miles from its aiming point, setting a new record in accuracy. On the first day, Surveyor VII radioed back over 21,000 photos of the surrounding highlands. Later, the surface sampler dug several trenches and also rescued the alpha-scattering instrument, which did not descend to the surface according to plan. The sampler was able to force it down to where it could make composition analyses.

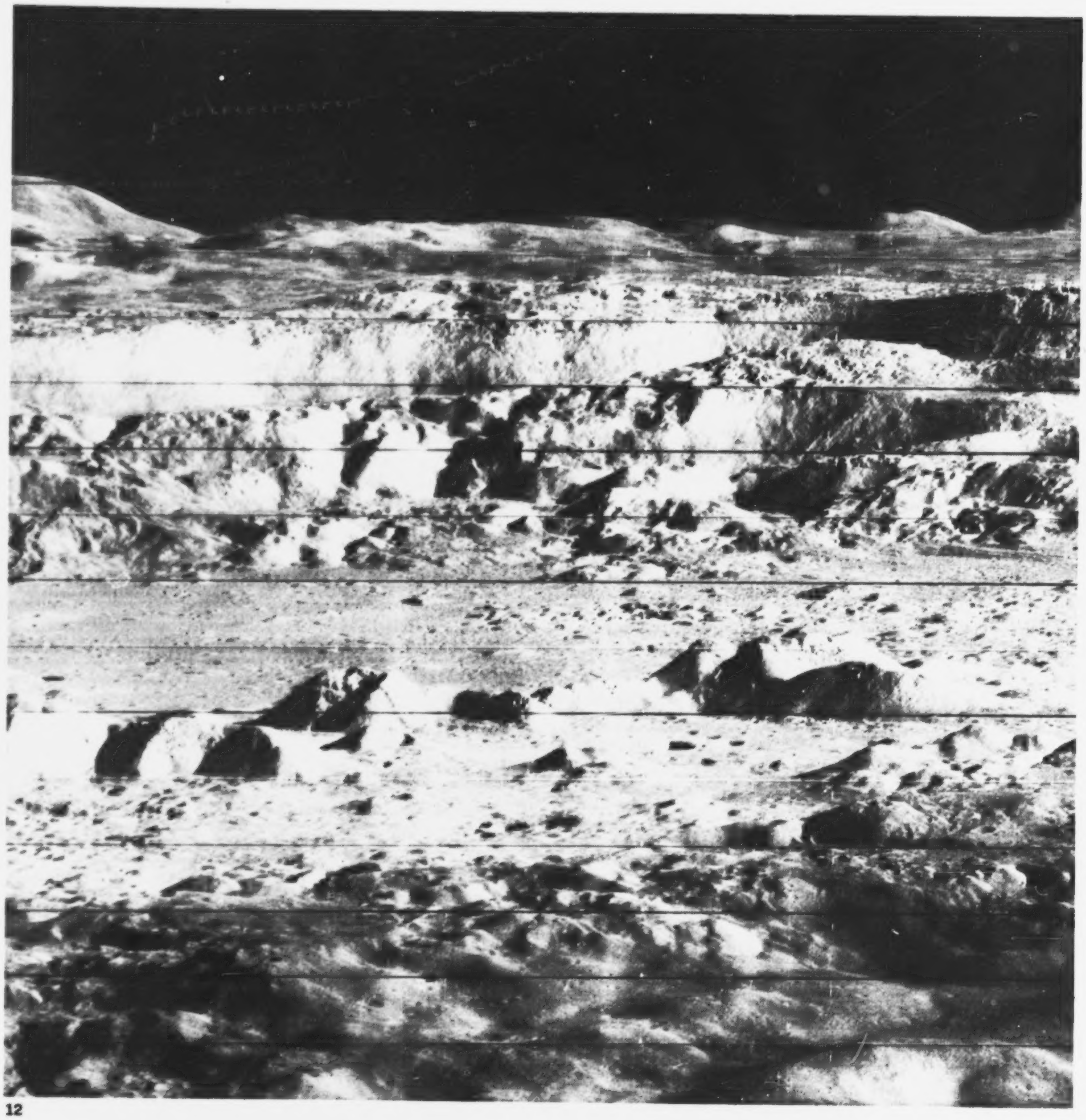
Through the telescope, Tycho seems a very young crater. Few later craters are superimposed upon it. Its rays radiate outward from the 56-mile crater, crossing many older lunar features. The Surveyor VII camera saw rocks everywhere—many more than previous Surveyors had seen on the maria. A further indication of Tycho's relatively recent formation was the fact that only a few inches of debris covered the surface around the spacecraft.

Some of the rocks photographed showed elongated spots up to a centimeter across. These may be mineral crystals. In some rocks, the spots line up in the same direction, just as crystals do in some terrestrial rocks. In other lunar rocks, the Surveyor VII camera showed two sets of elongated spots aligned in two different directions. In terrestrial rocks, this kind of structure indicates that the original rocks were altered after they solidified. Alteration or metamorphosis of rocks around Tycho could have come from the energy released during the collision or eruption that formed Tycho.

The alpha-scattering experiment on Surveyor VII made analyses of lunar highland material at three locations. The analyses showed that the material around the spacecraft contained lower percentages of the heavier elements, such as iron, than the mare materials. Neither mare nor highland materials are similar to the bulk of the meteorites picked up on the Earth's surface, inferring that meteorites probably do not originate on the Moon as some have supposed. The composition of the Moon also differs substantially from that of the solar atmosphere, indicating that the Moon, if indeed it was formed from solar material originally, has since undergone considerable chemical evolution.

Cameras In Lunar Orbit

For wide-scale, close-up mapping of the lunar surface, a lunar satellite is a must. The Rangers and Surveyors covered too small an area to give scientists a feel for the whole lunar surface. With this in mind, NASA's Jet Propulsion Laboratory (JPL), which built the Rangers, began studying picture-taking lunar satellites in 1959 as part of the Surveyor Program. Because JPL was too busy with the Rangers and the Surveyor soft landers, NASA transferred the Lunar Orbiter project to its Langley Research Center in 1962. The basic objective of Langley's Orbiter was to survey the Moon for possible Apollo landing sites. The program was extremely successful; the first three spacecraft obtained hundreds of superb photographs showing many places where astronauts could land safely. As a result of the success of the first three spacecraft, the objective of the remaining two flights was changed to that of obtaining high resolution photography of features on the entire front side of the Moon.



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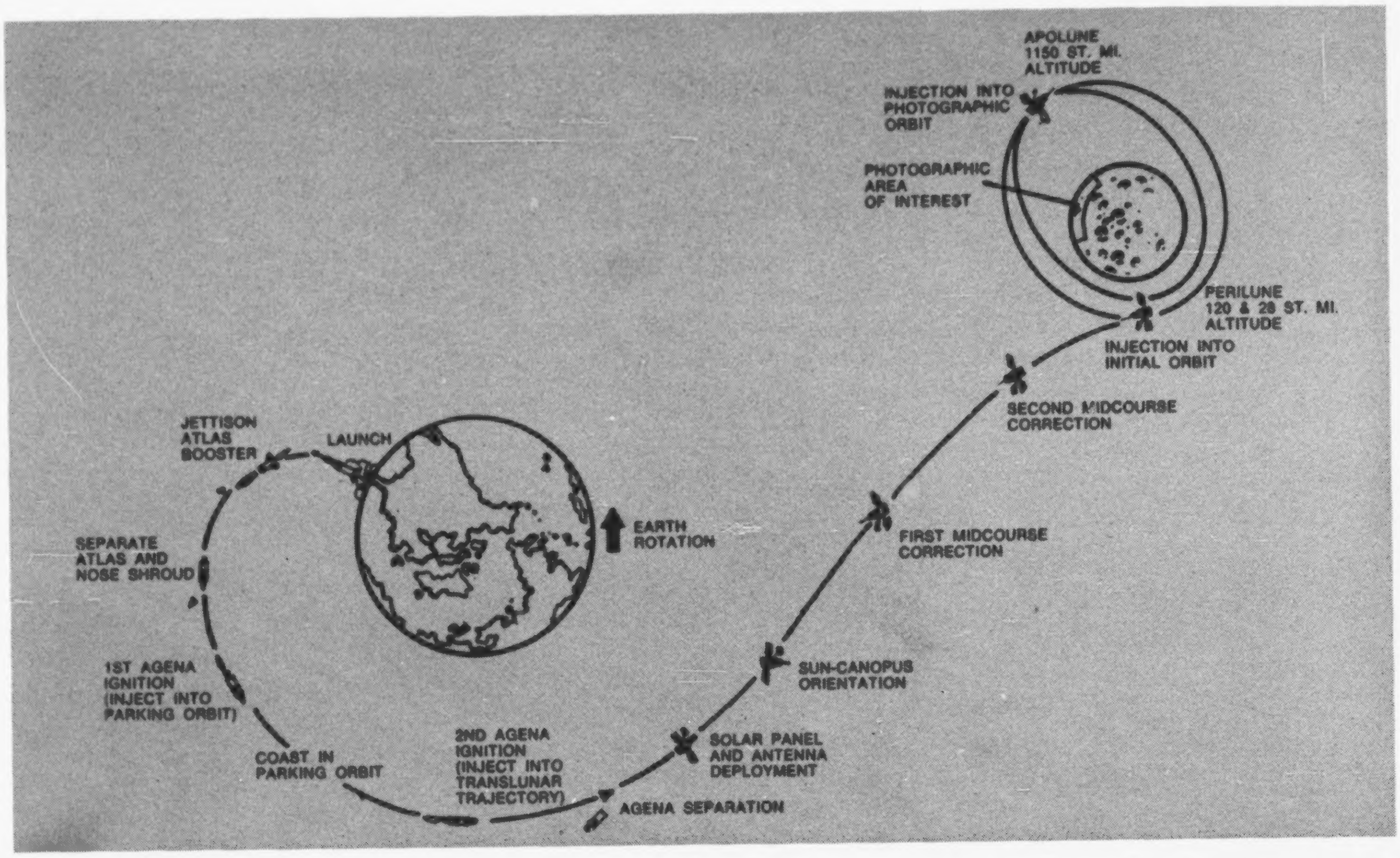
12 *Lunar Orbiter took this photo as it was approaching the crater Copernicus. Crater is about 60 miles across and two miles deep.*


APOLUNE
1150 ST. MI.
ALTITUDE
INJECTION INTO
PHOTOGRAPHIC
ORBIT
PHOTOGRAPHIC
AREA
OF INTEREST
PERILUNE
120 & 28 ST. MI.
ALTITUDE
INJECTION INTO
INITIAL ORBIT
SECOND MIDCOURSE
CORRECTION
JETTISON
ATLAS
BOOSTER
LAUNCH
EARTH
ROTATION
FIRST MIDCOURSE
CORRECTION
SEPARATE
ATLAS AND
NOSE SHROUD
1ST AGENA
IGNITION
(INJECT INTO
PARKING ORBIT)
SUN-CANOPUS
ORIENTATION
COAST IN
PARKING ORBIT
2ND AGENA
IGNITION
(INJECT INTO
TRANSLUNAR
TRAJECTORY)
SOLAR PANEL
AND ANTENNA
DEPLOYMENT
AGENA SEPARATION

13

The Lunar Orbiters overwhelmed scientists with sharp, clear photographs showing hundreds of thousands of square miles of the lunar surface in great detail. It will take years to analyze this bonanza completely.

The Lunar Orbiter pictures show that the Moon's surface is peppered with craters of every size, expanding the rather narrow views of the Rangers to the whole Moon. Apart from the craters, three general types of terrain remain: level, gently rolling, and rough. Most of the level ground occupies the dark plains of the lunar maria (seas). The gently rolling and rough countryside is found in the lunar highlands, where one finds a complex system of mountain ranges and intervening basins. In general, the maria seem concentrated on the side facing Earth—a puzzle to those who believe they were created by random meteor collisions.

When the entire collection of Lunar Orbiter pictures is viewed, it becomes apparent that lunar craters are not distributed randomly over the surface. There are obvious clusters. As noted in the Ranger photos, the bright rays of large craters show many small craters; which are often elliptical and oriented in the direction of the ray, like a school of fish. Population densities of craters between 30 and 60 feet in diameter vary from a high of 1700 per square mile to a low of 250. This nonrandomness could be due either to secondary craters created by ejecta from large craters or to internal volcanic action acting along lines of weaknesses in the Moon's basic structure. Probably both classes of events have occurred and may still occur.

As Lunar Orbiters flew over the Moon's highland areas found far fewer craters—a factor of 2 to 3 less than on the maria. This fact in itself cries for explanation. An even more striking aspect of the highland areas is the presence of narrow, roughly parallel ridges and troughs, a kind of washboard effect, with 10 to 30 feet between the crests. In some places the furrows are parallel to the general contours of the land; elsewhere this is not so. Sometimes the furrow-ridge systems intersect, giving a knurled appearance to the lunar surface. Probably these furrows are the result of subsurface activity associated with the lunar equivalent of Earthly mountain building.

A fascinating discovery from the Orbiter photography has been the detection of a few of what appear to be rare fresh craters, with all the marks of having been blasted out just yesterday. These fresh craters are sharp and distinct. Furthermore, sharp angular blocks are prominent on the floors and external slopes of the craters; some blocks have been blasted clear out beyond the crater in a ray-like pattern. Lunar specialists want to know what these blocks are made of. Are they from a debris-covered layer of lava or basalt? Or, are they just dust and debris welded together by pressure?

13 *Typical flight profile for a Lunar Orbiter. The flight to the Moon takes about 90 hours.*

The fact that fresh craters exist in the company of old craters infers the existence of some sort of weathering process on the Moon. Since the Moon has no weather as we know it, perhaps a steady rain of micrometeoroids knocks the fresh edges off craters in time. Only the fresh craters display angular, block-like rubble; will astronauts find similar blocks buried around old crater sites? If so, how did they get buried? And by what? Quite obviously, our closer look at the Moon raises questions we never thought of while looking through telescopes.

Some of the Moon's hot spots have been identified with fresh craters. It seems as if the impact of a meteoroid, or possibly a subsurface explosion, blasted off a layer of thermal insulation while making the crater. Fresh craters appear hotter than the surroundings because we see exposed the uninsulated, hot rock surface of the Moon. If this view is correct, we can imagine that today's hot spots will slowly be covered by dust—or whatever comprises lunar precipitation—and fade from our infrared pictures. After some millions of years, fresh craters may take on that worn, windblown look of the mare craters.

The subject of lunar craters is not as far removed from Earthly concerns as we might like to think. There are enough fresh craters on the Moon to tell us that large meteoroids are still colliding with the Moon (assuming they are meteoroid craters of course). If large meteoroids collide with the Moon, they can also hit the Earth. Is Meteor Crater, in Arizona, a fresh terrestrial crater corresponding in time to those fresh craters we see on the Moon? Perhaps the Earth and Moon survived the same celestial cannonades and the Moon can give us hints about the Earth's past and future.

An intriguing feature from the Orbiter photographs: several of the pictures provide strong indications that material has flowed down the sides of some craters. There is clear evidence of what terrestrial geologists call "mass wasting"—that is, dirt, rock, or something flowing down hill. On Earth, both lava and water-saturated soil flow down hill. We might expect lava on the Moon—but water? Unlikely as it may seem, some scientists feel that ice may still survive under the insulating dust that seems to cover most of the Moon. Lunar mass wasting might occur as dust-covered ice moves glacier-like down slopes.

The Planets

Beyond the Moon, eight planets and numberless planetoids and asteroids ply their elliptical paths around the Sun. The planets, in particular, attract us. Through the telescopic eyepiece, they seem to float tantalizingly in space—so near yet so far. Though we know now that these distant worlds are inhospitable to our form of life, they are our closest neighbors in a universe that otherwise seems very empty. Perhaps they harbor life forms adapted to their extreme environments; or we may find remnants or precursors of life.

Mars has always been a favorite target of the astronomer's telescopes. Rich surface detail swims frustratingly in and out of the observer's ken. Some astronomers see a Martian surface covered with a gridwork of artificial-looking lines; others see nothing or a few smudges at best. Most agree, however, that a peculiar wave of darkening sweeps toward the equator following the shrinking of the polar caps in the Martian springs. Clouds are also observed, indicating the presence of an atmosphere. In fact, Mars looked so obviously inhabitable to early observers, especially Boston's Percival Lowell, that they scarcely doubted that it was inhabited. Modern telescopic studies reveal a much less inviting planet—a frigid spheroid where temperatures at the equator barely get above freezing during the hottest summers, and a thin atmosphere, mostly carbon dioxide, only one-fortieth the pressure at the Earth's surface.

Mars is a little too far away for today's radar to be of much use in probing its surface. It is the planet Venus that yields to radar interrogation. This is fortunate because Venus is so shrouded by clouds so heavy that astronomers never catch even fleeting glimpses of anything below. By choosing the proper frequency, radio pulses can be reflected directly from Venus' solid surface. Venus also emits radio waves that help us diagnose its atmospheric structure and temperature; however, these radiations are subject to wildly varying interpretations.

Beneath all the clouds, Venus is about the size of the Earth, but since we cannot see the surface, we cannot guess its topography nor even deduce from visual data alone how fast it rotates on its axis. The Irish planetologist, Patrick Moore, once counted all the guesses of the rotational period of Venus made from 1666 to 1961 and came up with 85, ranging from about 22 hours to 225 days.

Radar offers a way to determine the rate of rotation of a planet even if the surface cannot be seen. If a pulsed radar signal of a given frequency is transmitted toward a planet, the echo will be spread out both in time and in frequency. The first part of the echo was reflected back from the nearest part of the planet and the tail of the echo from more distant parts of the planet. The spread in frequency is a Doppler effect produced by the relative motions of the planet and the Earth, including the rotation of the planet. If, for a given portion of the tail of the echo, the spread in frequency of the echo is plotted for various positions of the planet in its orbit, both the direction and rate of rotation of the planet can be calculated.

The first radar contacts with Venus were made in 1961. These echoes were too weak to determine the planet's rotation. More powerful radar systems were used during subsequent years. By watching the shape of the echo signal, radar astronomers decided that Venus rotates on its axis only once every 240 to 250 days and that it rotates the wrong way; that is, its rotation is retrograde, opposite to the rotations of all the other planets. The exact rate of rotation has been determined by another use of radar. Today's radar is good enough to distinguish rough spots on the planet's disk. It is assumed that these rough spots are true surface features, such as mountains, and not atmospheric phenomena. By watching the movement of these features over long periods of time, the rate of rotation of Venus is known to within an hour or so.

The temperature of Venus' unseen surface is also a subject of controversy. The temperature of a planet can be deduced from the electromagnetic radiation it emits. In the case of Mars, surface temperature is easy to measure because we can look directly at the surface with an infrared detector. The temperature of the invisible surface of Venus can be inferred in two ways: (1) by direct measurement of surface radiation in the microwave region of the spectrum which may pass through the cloud cover unaltered; and (2) by measuring the temperature of the top of the cloud layer and making assumptions about how temperatures vary below. The first supposed temperature measurements of Venus' surface were made in 1924 in the 8-13 micron* infrared band which represents a spectral window in the Earth's atmosphere. The result was a chilly –28°F. But the clouds of Venus are apparently not transparent in the infrared, and the –28°F turned out to be only the temperature of the atmosphere far above the surface. When temperature measurements were made in the microwave region in 1956, a startling 800°F was measured. More microwave measurements confirmed a hot rather than cold Venus. Visions of a life-sustaining planet vanished as scientists pictured a baked surface, possibly spotted with lakes of liquid metal.

Venus did not stay hot for long. In thick atmosphere continuously stirred and activated by the Sun, nonthermal radiation is quite possible in the microwave portion of the radio spectrum; glow discharges and similar electrical activity might radiate microwaves that would make Venus appear hotter than it is. Some experimenters measuring Venus' radio emissions in 1966 estimated that 30% of the radio energy they received was probably nonthermal. This viewpoint brought the surface temperatures of Venus down so far that seas of ordinary water and even polar ice could exist. Today, however, most observers of Venus feel that nonthermal microwave radiation is negligible. The temperature question is still not settled.

Flying By Venus

Why fly by Venus instead of going straight in through its atmosphere for a hard or soft landing? Surveyor-type soft landings have been out of the question until recently because operational booster rockets were not

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* *A micron is one millionth of a meter.*

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14 *Mariner II, a Venus probe.*

large enough to propel a heavy soft lander to Venus. Hard landings are possible, but the high temperatures create a big question mark.

During a flyby, the space probe spends hours in the vicinity of the planet. During flight, mission controllers on Earth fire the probe's midcourse motor by remote control so that its trajectory takes the spacecraft around back of the planet. In this way, radio signals from its transmitters are temporarily cut off (occulted) by the solid planet and its atmospheric layer. By measuring how the transmitter's radio waves interact with the atmosphere, scientists can infer the atmosphere's density, height, and degree of ionization. Magnetometers and radiation detectors on a flyby probe can look for a magnetosphere and radiation belts. Further, the planet's disk can be scanned by radio and optical instruments. The cloud cover of Venus prevents visual surface photography, but microwave and infrared pictures of the planet can tell us something about its atmosphere—much more than we can learn with the same instruments from the Earth tens of millions of miles away.

The U.S. interplanetary program has resided at the Jet Propulsion Laboratory in Pasadena ever since NASA assumed responsibility for nonmilitary space activities in 1958. The JPL planetary probe program was called Mariner. Early plans called for launching a probe to Venus and another to Mars in the 1962-1964 period when both planets would be in favorable positions relative to the Earth. The first good Venus firing window extended 56 days between July and September 1962. JPL prepared two probes, based to some degree on its Ranger technology. The first, Mariner I, was launched July 22, 1962, but had to be destroyed by the Cape Kennedy safety officer when it veered off course. Mariner II was successfully launched toward Venus on August 27, 1962. 109 days later, and 36,000,000 miles from the Earth, Mariner II passed within 21,598 miles of Venus.

Mariner II weighed only 447 pounds, including a rocket for midcourse corrections, a power supply, controls, transmitter, and so on. It also carried a microwave radiometer,* an infrared radiometer, a

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** A radiometer measures the intensity of electromagnetic radiation within a narrow bandwidth.*

15 *The trajectory of Mariner V. (See page 22 for details of the encounter with Venus.)*

magnetometer, radiation counters, a micrometeoroid detector, and a solar wind detector for measurements of interplanetary space on its way to Venus.

The magnetometer on Mariner II found that the magnetic field of Venus was zero or at most very small. Neither were any untoward concentrations of radiation and solar plasma discovered. And Venus did not seem to be surrounded by a micrometeorite or dust cloud like the Earth.

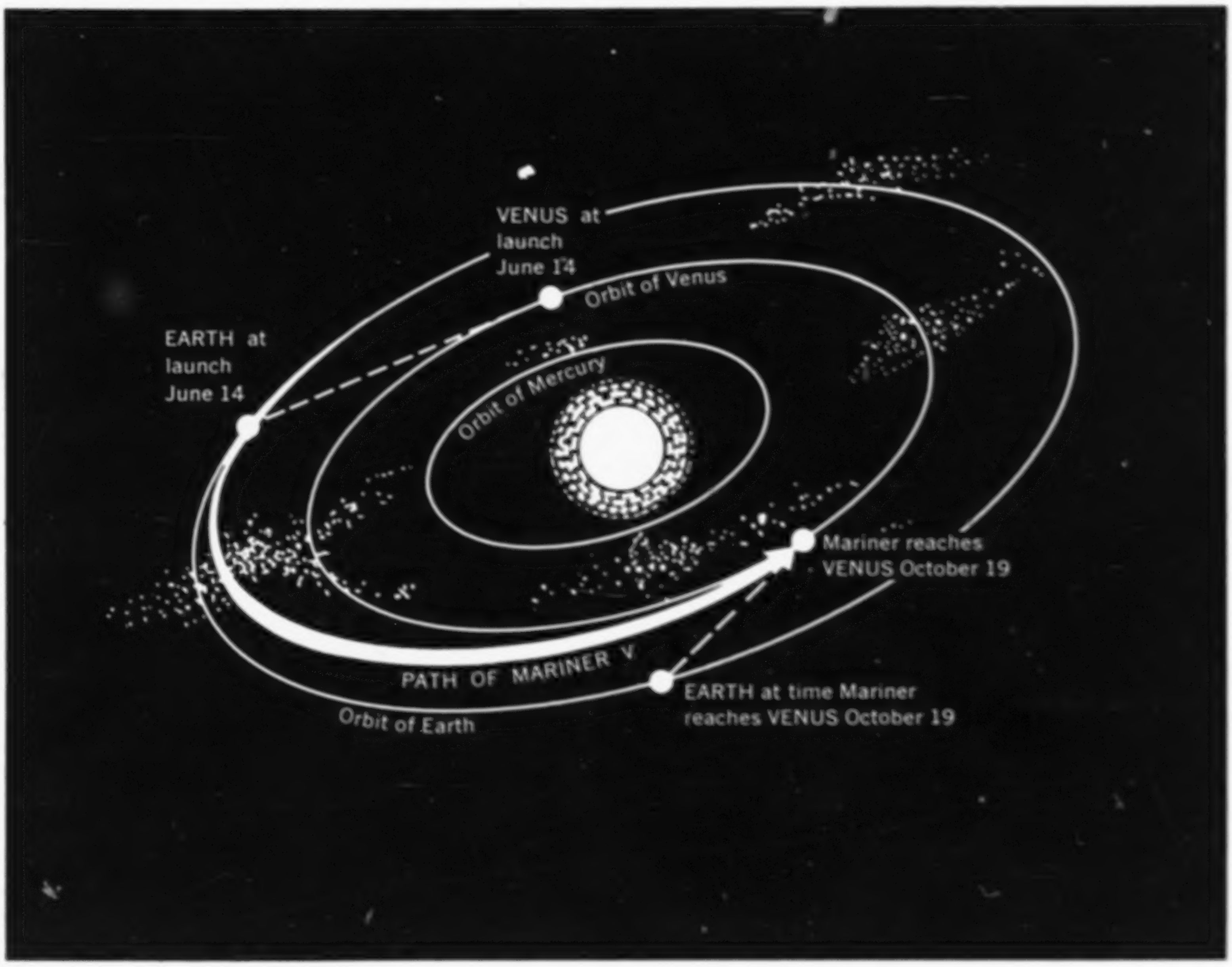
The nearness of Mariner II to Venus allowed its two radiometers to scan the disk of Venus, covering both the night and day areas. As the radiometer's field of view moved toward the edge of the planet, it saw less and less planet and more and more atmosphere. The atmospheric edge of the planetary disk is called its "limb." Thus, Mariner II radiometers could measure the fine structure of the planetary disk, something impossible for Earth-based radiometers.

The microwave radiometer gave scientists their first close-up temperature readings. Eighteen readings were made at both 13.5 and 19 millimeters as the radiometer scanned the planet. According to the telemetry data, the surface of Venus was extremely hot—about 800°F, assuming, of course, no nonthermal radiation. As the radiometer scanned close to the edges of the planet, limb darkening was noticeable. This infers that the microwave radiation came mainly from the planet's surface rather than its atmosphere. (Limb brightening would have inferred the reverse situation.) Moreover, little change in temperature was noted as the scan crossed the dividing line (the so-called terminator) between dark and sunlit sides. The conclusion drawn from this was that strong convection within the atmosphere of Venus equalized temperatures between day and night sides.

Slight limb darkening was observed by the infrared radiometer, which measured radiation at 8.4 and 10.4 microns. Since carbon dioxide absorbs infrared radiation in the 10 micron region, scientists interpreted this result as indicating a small amount of carbon dioxide above the tops of the thick clouds of Venus. In summary, Mariner II results supported the hot Venus viewpoint.

Venus was untroubled by snooping probes from Earth for nearly five years. Then, within two days in October 1967, two probes flew past, carrying different complements of instruments. One was Mariner V (Mariners III and IV were Mars probes); the other was Venus 4 (Venera 4), a spacecraft launched by the U.S.S.R.

Venus 4 arrived a day before Mariner V. It carried a magnetometer that detected no measurable field in the neighborhood of Venus, a result that conflicted with Mariner V data. The primary contribution of the Soviet experiment was in the direct measurement of atmospheric temperature, pressure, and composition during the hour and a half descent of its parachute


VENUS at launch June 14
Orbit of Venus
EARTH at launch June 14
Orbit of Mercury
Mariner reaches VENUS October 19
PATH OF MARINER V
EARTH at time Mariner reaches VENUS October 19
Orbit of Earth

15

instrument capsule through about 15 miles of atmosphere.

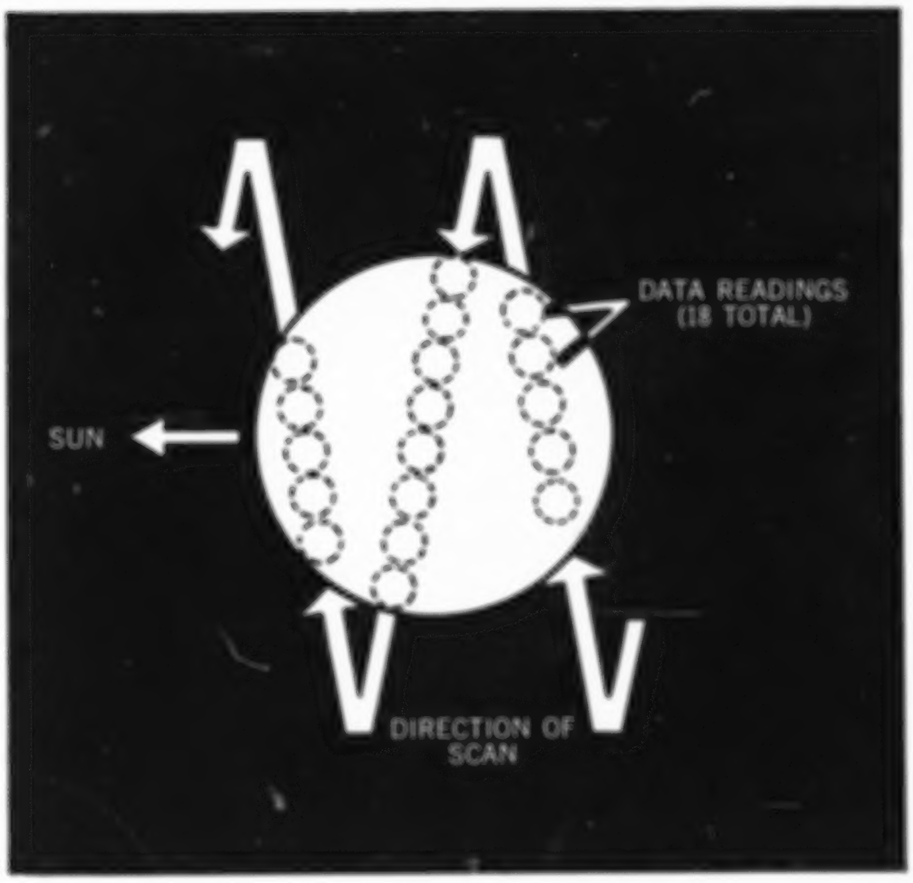
On October 19, 1967, Mariner V flew past Venus some 6300 miles from the planet's center. It carried a solar wind detector, radiation counters, an ultraviolet photometer, and two radio occultation experiments. The experiments of Mariner V were basically different from those of Venus 4, although we should expect agreement where the phenomena measured overlap. While the results do not all concur exactly they are generally not contradictory.

In summary, Mariner V, like Venus 4, found a hot planet with a thick atmosphere—mostly carbon dioxide (about 80%). It found an ionosphere, an induced magnetosphere, a "plasmapause," and a "superrefractive" atmosphere. Scientists are still analyzing the immense quantity of data telemetered back by Mariner V, and conclusions must be considered tentative. The Mariner V picture is drawn in terms of the electromagnetic effects observed from outside the Venusian atmosphere, while the Soviets made direct measurements of chemical and thermodynamic quantities in the atmosphere down to or near the surface. It is not really surprising that two rather different pictures are seen viewed through such different sets of instruments.

According to Mariner V, an intrinsic magnetic field of Venus exists but seems to be a thousand times smaller than the Earth's. Even with only a small magnetic

16 *The scanning platform on Mariner II made three passes at the disk of Venus with microwave and infrared radiometers.*

17 *Venus 4 measured pressure and temperature during its descent through the atmosphere of Venus.*



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field, the solar wind seems to flow around Venus. The deflecting prow of Venus is its newly discovered, dense ionosphere. The outer surface of this prow is termed a plasmapause to distinguish it from the Earth's magnetopause, which deflects the solar wind for our planet. The plasma in the ionosphere inside the plasmapause is so good an electrical conductor that magnetic fields cannot penetrate it in either direction. It therefore traps internally generated lines of force and excludes those in interplanetary space.

The superrefractive atmosphere of Venus is bizarre. Venus' atmosphere is so thick that electromagnetic waves entering it from outside at certain angles are apparently trapped and cannot leave again, much as some terrestrial radio waves are trapped between the Earth's surface and ionosphere. The full physical implications of this radiation trap are not known as yet, although we can surmise that the horizon would seem to curve up to anyone standing on the surface of Venus.

There is no accepted view of Venus. The space probe data are too new. Add its retrograde rotation and we have a Venus that a 1958 scientist would have thought unlikely—as improbable, say, as a Mars pockmarked with craters like the Moon.

Where Are The Canals?

"The Planet Mars, a Second Earth" was the title of a book written by Jakob Schmick, a German scientist, as the Nineteenth Century drew to a close. The title reflects the thought of that era: Mars was assuredly an abode of life. When the American astronomer

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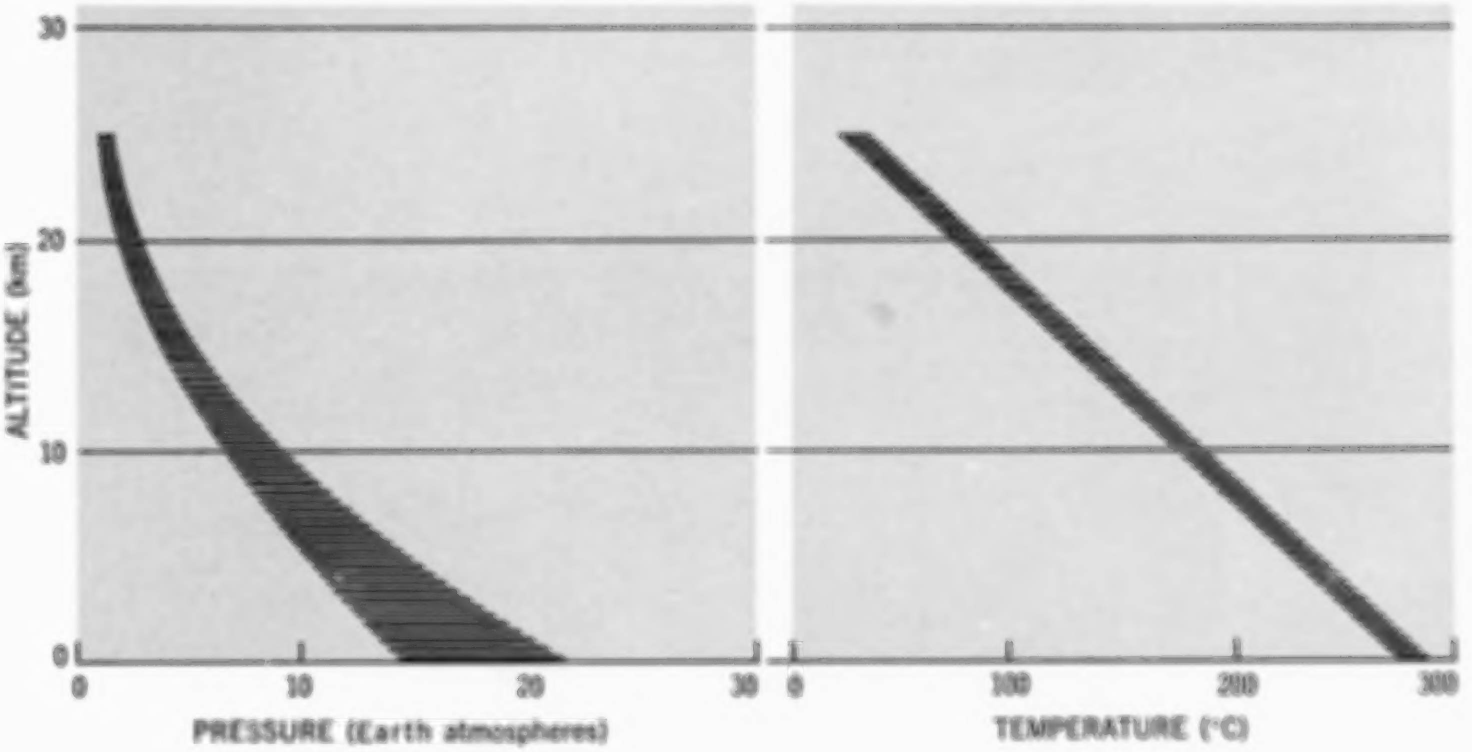


Percival Lowell began publishing popular accounts of his studies of the Martian canals ("Mars and Its Canals," 1900), he merely reinforced current opinion. Many top astronomers, however, could not see any canals at all, much less the intricate, intelligently organized network that Lowell drew. Slowly, the Martian canals and the expectation of finding life on Mars faded into the background of World War I and other urgent matters. But, half a century later, when the first space probe was launched toward Mars bearing a camera, keen anticipation was felt by the pro-life and anti-life schools and those of the pro-canal and anti-canal persuasions. These controversies are still deeply ingrained in the fabric of today's speculations about Mars.

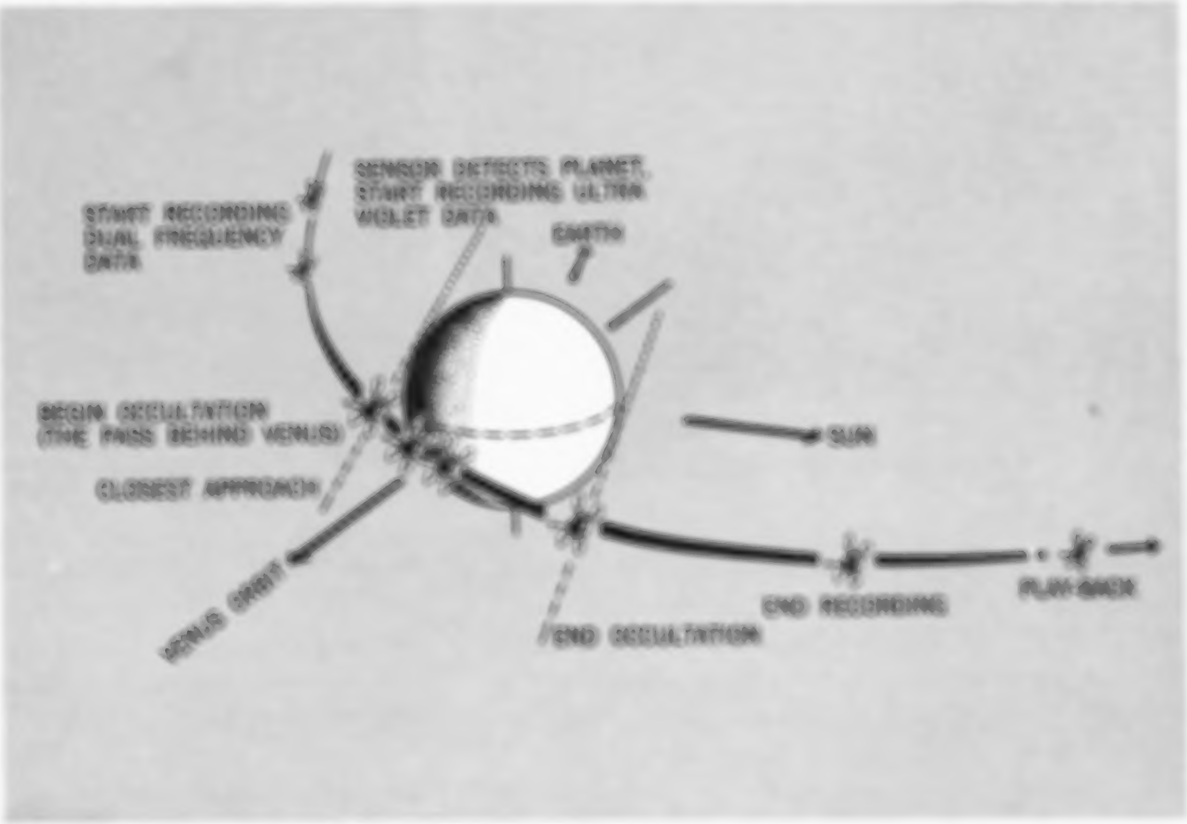
Mariner IV has been the only successful Mars probe, as contrasted with three for Venus. The innate perversity of machines seems to have been the problem rather than lack of trying. Mariner III, for example, was launched toward Mars on November 5, 1964, but the spacecraft's protective shroud could not be blown off after launch. Russia has made several tries, but only one, Zond 2, launched November 30, 1964, has been officially announced. Zond 2 failed to return any data on Mars.

The payload on Mariner IV was much like that of Mariner V, the Venus probe. The major difference was the addition of a television camera on the scanning platform. Close-up pictures were the primary goal; but radiation detectors, a magnetometer, a solar wind detector, and a micrometeoroid detector were also aboard. As the spacecraft passed behind Mars, occultation of its telemetry transmitter signal was observed on Earth, yielding information on the planet's atmosphere and ionosphere.

Mariner IV encountered Mars on July 15, 1965, after a flight of 307 days. The probe came within

18 *A typical planetary encounter.*
Mariner V flew past Venus on October 19, 1967, 127 days after launch. As it passed behind the planet, the probe's radio signals were modified in their passage through the planet's thick atmosphere. These changes permitted scientists to deduce the nature of the atmosphere and ionosphere of Venus.

19 *Mariner IV being prepared for a 350 million mile space voyage to the vicinity of Mars.*

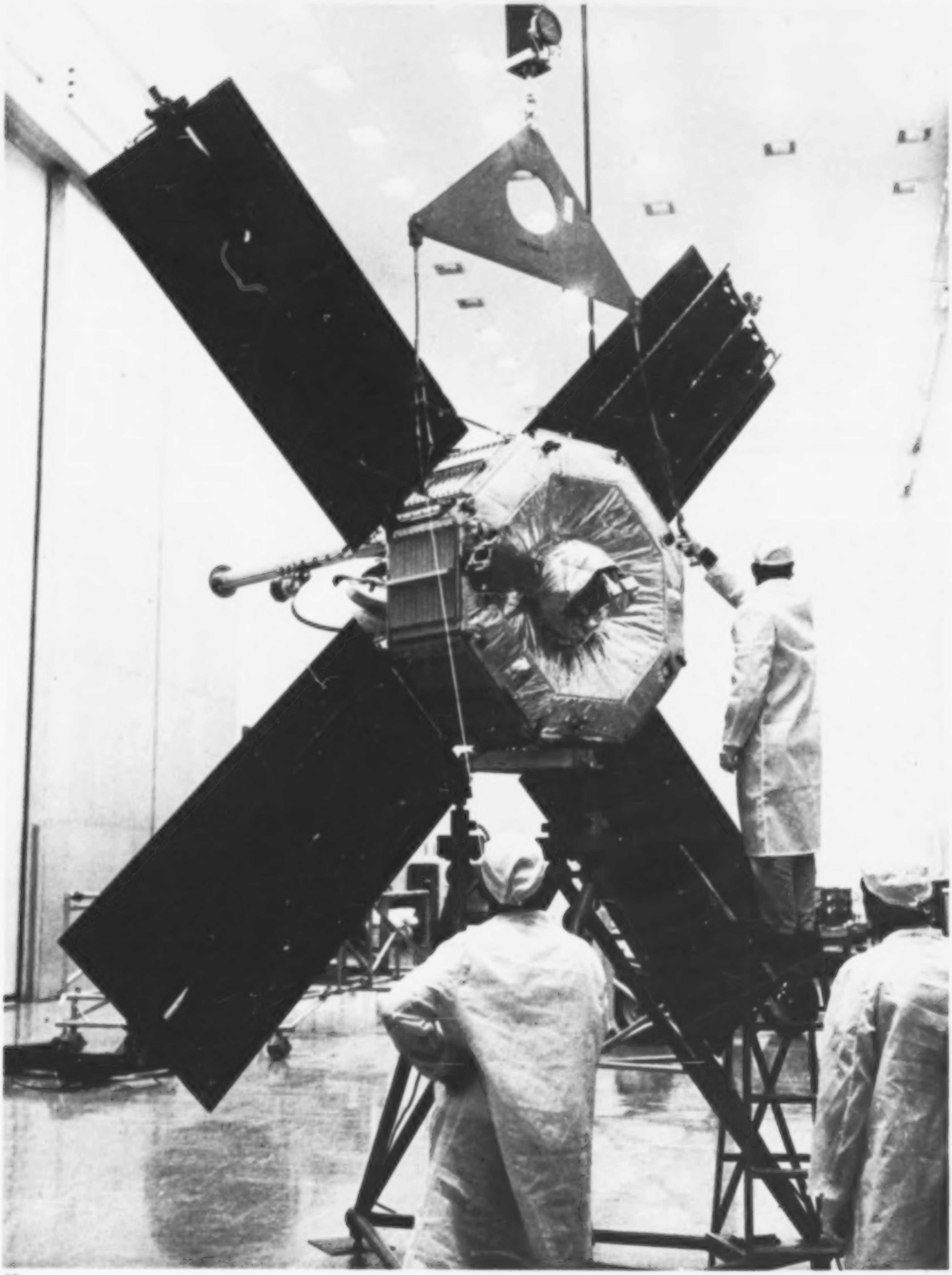

START RECORDING
DUAL FREQUENCY
DATA
SENSOR DETECTS PLANET,
START RECORDING ULTRA
VIOLET DATA
EARTH
BEGIN OCCULTATION
(THE PASS BEHIND VENUS)
SUN
CLOSEST APPROACH
VENUS ORBIT
END OCCULTATION
END RECORDING
PLAY-BACK

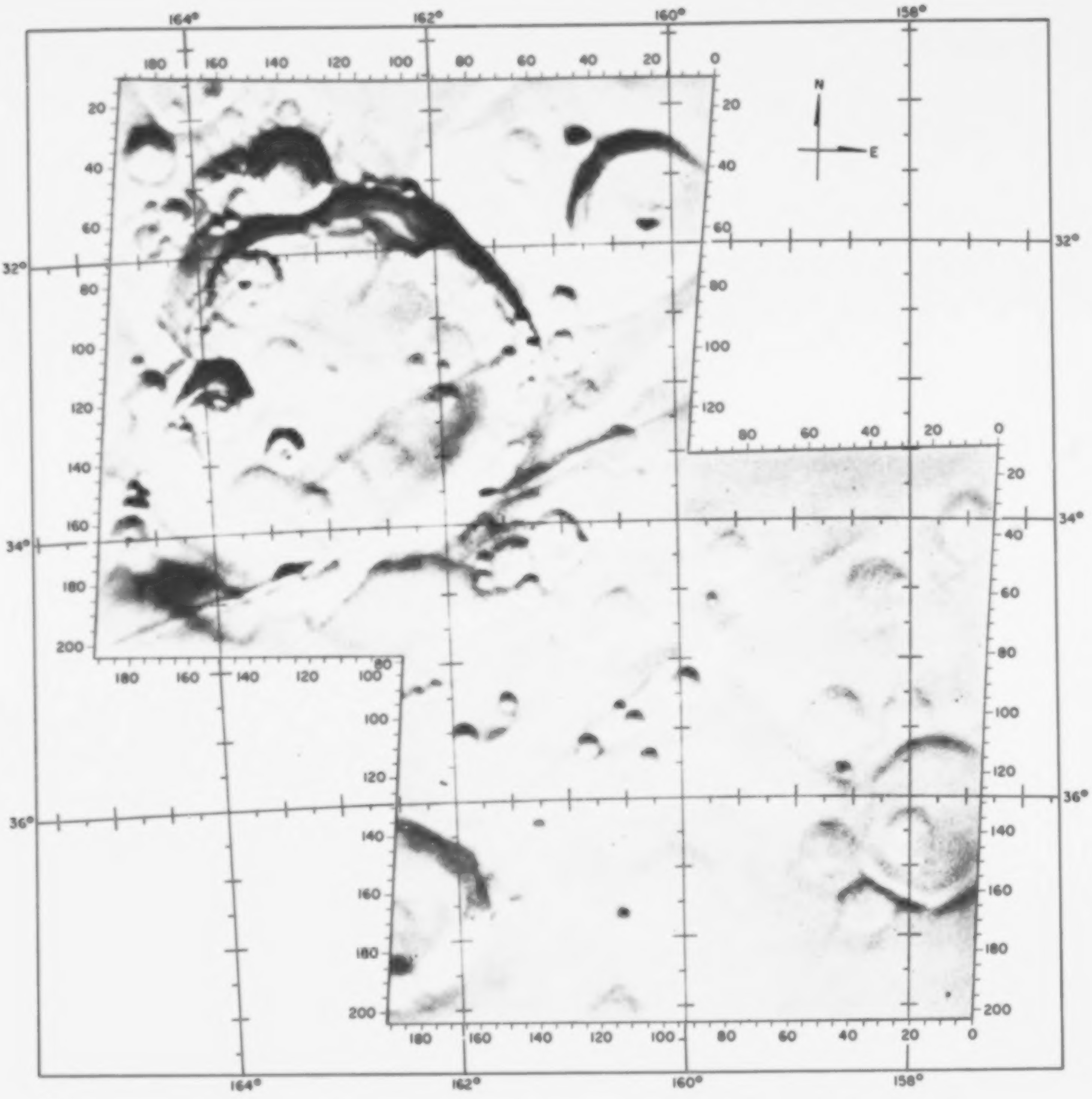
18

6200 miles of the planet and transmitted its findings back to Earth, by that time some 135,000,000 miles away.

The close-up photos of Mars looked as if they might have come from a Lunar Orbiter. They were fuzzier, to be sure, but the terrain surveyed strongly resembled that of the Moon. A few scientists, such as Ernst Opik and Clyde Tombaugh, had predicted a heavily cratered Mars as early as 1950; but most of the scientific world was taken by suprise. The 21 Mariner IV pictures clearly showed about 100 craters along the long narrow strip of the planet it surveyed. The craters seem remarkably Moon-like; some even have that peculiar little mountain in the center of the crater. From the small sample taken, Mars may have 10,000 craters with diameters between 3 and 75 miles. The Martian surface appears very old. The rate of weathering can be guessed by studying the craters, but estimates vary widely. Weathering is certainly faster than on the airless Moon, but undoubtedly much slower than on Earth, where most craters were all but obliterated by erosion long ago.

The big questions, of course, are: Where are those canals and are there any signs of life?





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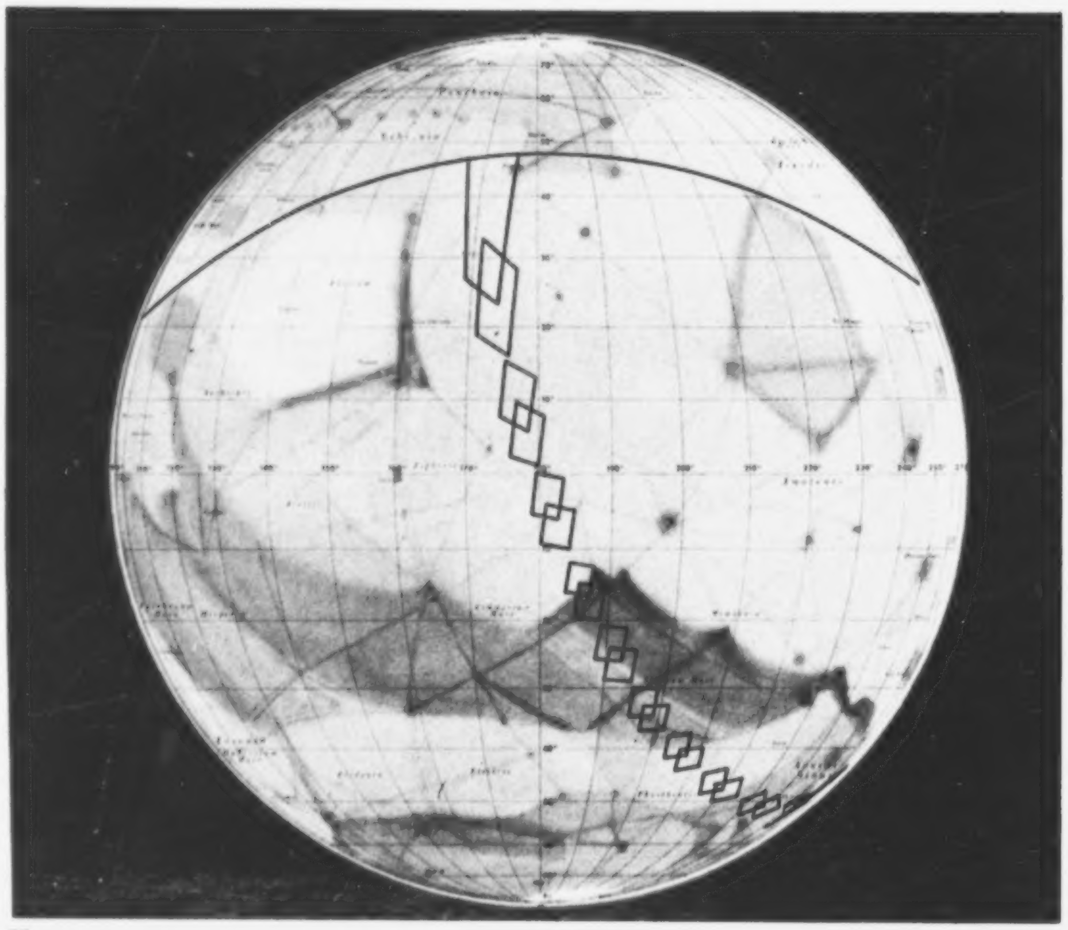
At first glance, the canal scoffers seemed about to have their victory. Canals are certainly not obvious. A more careful analysis—with an open mind, of course—reveals several linear features. Some astronomers have found straight-line features in the photos, which they can associate with canals seen from Earth. The linear features seen by Mariner IV may represent well-weathered and pock marked natural geological features—perhaps natural cracks in the plant's crust caused by meteoroid impacts.

As for life, we cannot see buildings, roads, forests, or any other features, suggesting any kind of life. But from 6200 miles, we shouldn't. Careful analysis of similar pictures taken from high Earth satellites—with better detail—show no conclusive signs of any kind of life on Earth.

The other experiments on Mariner IV discovered some important features of the planet. Mars has no

20 *Airbrush drawing of Mariner IV photos 11 and 12, showing the heavily cratered Martian surface. Careful analysis and interpretation of photo 11 (top) reveals many more craters than revealed in a cursory examination of the original photo. A strong linear feature is also shown approximately in the location of a Martian canal. These linear features are probably due to natural geological processes, such as those that form rift valleys on the Earth.*

21 *The pictures of Mars transmitted from Mariner IV showed the areas indicated on this map. Sequence was from top to bottom; photos on page 24 are part of this sequence.*



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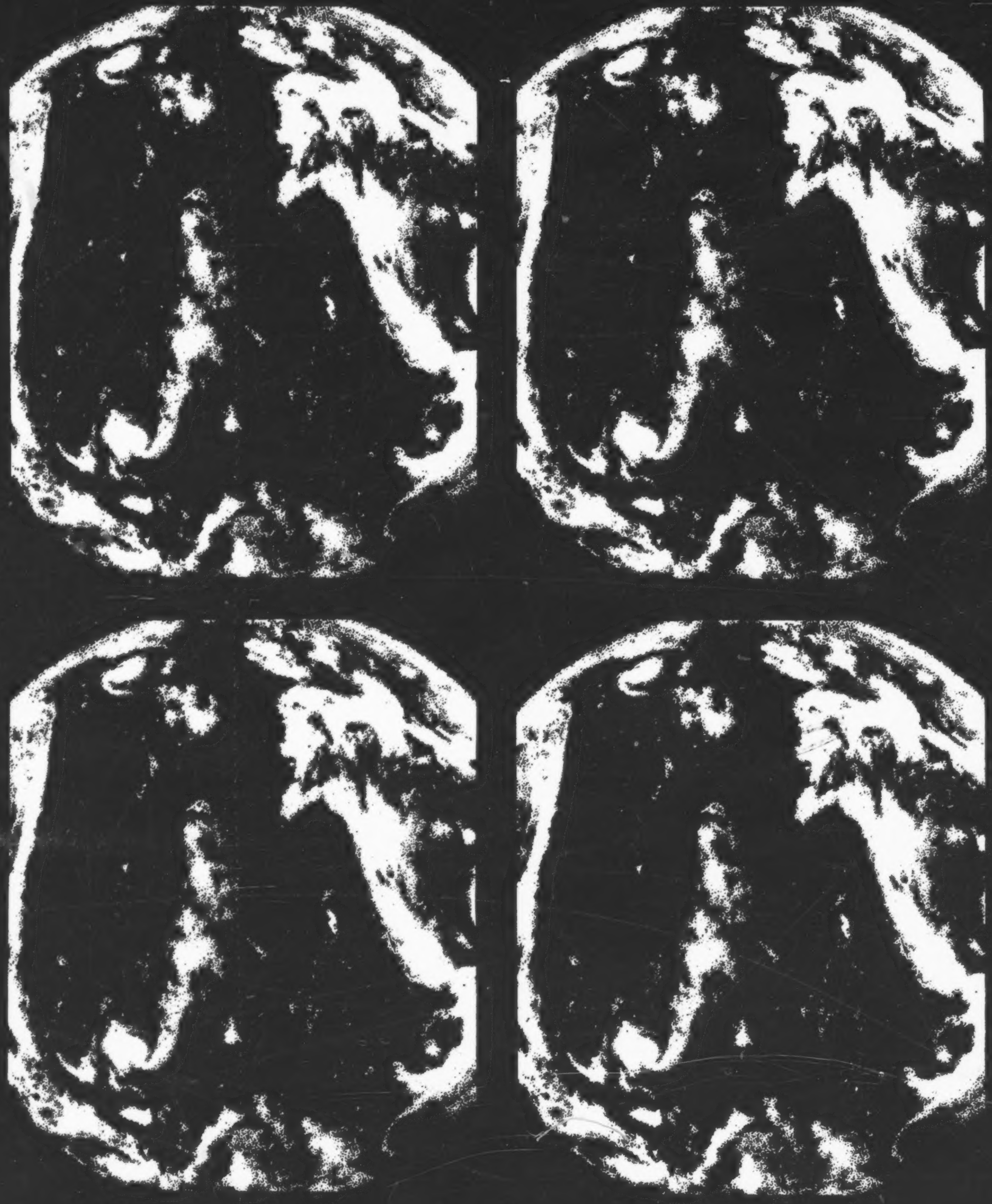
significant magnetic field of its own and no radiation belts. The atmosphere is even thinner than that deduced from terrestrial observations: 4 to 7 millibars, mostly carbon dioxide and argon. (Atmospheric pressure on Earth is about 1000 millibars.) Sunlight acting on the thin film of atmosphere hugging the planet does not create an ionosphere on the Sun side. Apparently, the solar wind slams directly into the atmosphere, creating a bow shock wave as it does with the Earth's magnetopause and Venus' ionosphere.

More than ever, Mars seems hostile to life. But not completely so. Some form of life could conceivably hang onto existence on that desolate cratered surface. At some period in its early history, Mars may have had an atmosphere more conducive to life. Traces of such life may be found there by future probes.

America In Space | The First Decade

Putting Satellites To Work



National Aeronautics and Space Administration

**America
In
Space:
The
First
Decade**

This is one of a series of booklets published on the occasion of the 10th Anniversary of the National Aeronautics and Space Administration.
These publications are not intended to be comprehensive history, nor do they deal with all the facets of NASA's aeronautical and space activities. Rather they are overviews of some important activities, programs and events written for the layman in terms of the several science disciplines.

Each of these subjects is treated in more depth in other NASA publications and in scientific journals.

1 October 1968

Titles in this series include:

I Space Physics and Astronomy
II Exploring the Moon and Planets
III Putting Satellites to Work
IV NASA Spacecraft
V Spacecraft Tracking
VI Linking Man and Spacecraft
VII Man in Space

Others are in preparation. Topics include:

Propulsion
Spacecraft Power
Space Life Sciences
Aeronautics
Space Age By-products
Materials

PUTTING SATELLITES TO WORK

by William R. Corliss

National Aeronautics and Space Administration, Washington, D.C., 20546

Introduction

Ten years ago NASA was brought into being to explore space. As stated in the National Aeronautics and Space Act of 1958: ". . . it is the policy of the United States that activities in space should be devoted to peaceful purposes for the benefit of all mankind." One of the major avenues of intellectual and program effort that has guided us at NASA has been the concept, at first unproved but now clearly valid, that space systems can provide unique, direct benefits to man, benefits not before possible or economically feasible.

We do not yet know the full range and scope of the possibilities that spacecraft open for the service of man. Those few particular applications upon which we have concentrated in the past and which are described in "Putting Satellites to Work" have borne out that promise. Communications, navigation, geodetic, and meteorological space systems are operational today, and their existence, once the subject of science fiction, is now a practical fact. It is clear that many potential applications exist: the one most clearly on the horizon is the possibility of surveying the Earth's resources from space. We are really just beginning to develop the possibilities in this area of research, but we can clearly foresee that during the next decade NASA can, in building on its past accomplishments, provide tools which may significantly affect the efficiency and thus the quality of our life here on Earth.

Leonard Jaffe
Director, Space Applications Program

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Putting Satellites To Work

The Weather Watchers

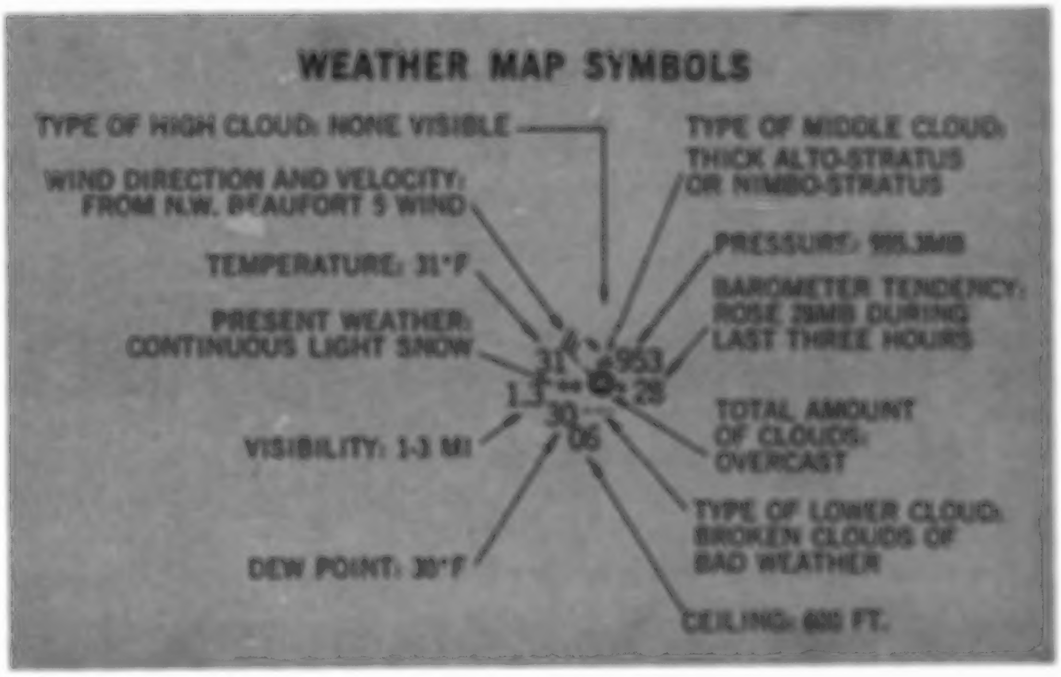
A Better View of the Weather

Good weather forecasting is worth money. An accurate five-day forecast would probably save between $2.5 and $5.5 billion yearly in the U.S. alone; perhaps $15 billion for the entire world. Most of the savings would be in agriculture, the construction industry, and government operations, such as flood control. The capital investment for a good global weather forecasting system should cost less than a half billion dollars; the potential payoff is impressive.

Besides the time-honored approach of watching the skies for weather signs, what can we do to improve weather forecasting? Four possibilities come to mind, and we have been trying all four for over a century:

1. Rather than looking for red sunsets or mackerel skies, we can record more objective data. Examples are: temperature, wind direction and velocity, humidity, and so on. These are all classical measurements that have been recorded regularly at weather stations since the early 1800s.
2. A weather station operator can expand his fund of basic information further by lofting instruments on balloons, or, as was popular in the last century, by flying them on large kites. Better knowledge of the air aloft leads to a better understanding of what is happening to air close to the ground.
3. As meteorologists realized that weather patterns were actually continent-sized rather than local in nature, they began to link individual weather stations into networks. Just before the Civil War, Joseph Henry, of the Smithsonian Institution, began to collect weather observations taken concurrently over a broad area. This *synoptic* information was relayed to Henry by telegraph from stations all over the eastern U.S. Now, many countries have well-integrated networks of stations and there is considerable international exchange of weather data.
4. Another improvement in weather forecasting has come as meteorologists have learned more about the natural forces that actually make weather. Representing these forces mathematically, they have constructed equations that describe the movements of weather fronts and the mechanism of the hurricane. By feeding these equations into a high speed computer and adding the data taken by weather stations and weather satellites, meteorologists believe they can eventually generate accurate two-week forecasts.

Long before the National Aeronautics and Space Administration was conceived, sounding rockets were contributing to our knowledge of the upper atmosphere. NASA, of course, has continued this line of attack, but the Earth satellite is the most valuable meteorological tool contributed by the space program. Like


WEATHER MAP SYMBOLS
TYPE OF HIGH CLOUD: NONE VISIBLE
WIND DIRECTION AND VELOCITY: FROM N.W. BEAUFORT 5 WIND
TEMPERATURE: 31°F
PRESENT WEATHER: CONTINUOUS LIGHT SNOW
VISIBILITY: 1-3 MI
DEW POINT: 30°F
TYPE OF MIDDLE CLOUD: THICK ALTO-STRATUS OR NIMBO-STRATUS
PRESSURE: 995.3MB
BAROMETER TENDENCY: ROSE 2.8MB DURING LAST THREE HOURS
TOTAL AMOUNT OF CLOUDS: OVERCAST
TYPE OF LOWER CLOUD: BROKEN CLOUDS OF BAD WEATHER
CEILING: 600 FT.
31
953
1.3
28
30
06

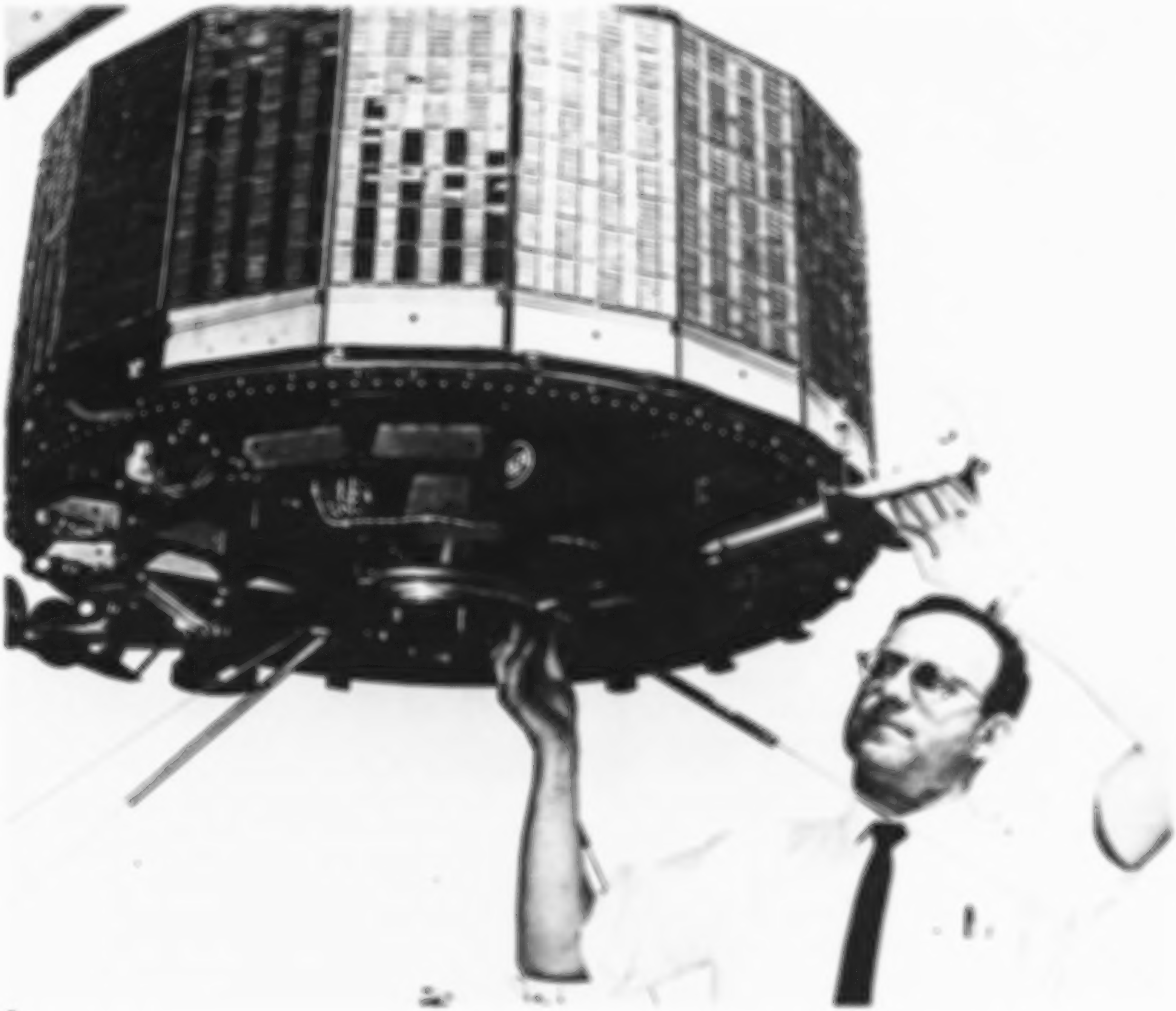
1

1 A surface weather station usually records only highly localized information. Station networks extend coverage geographically. Satellites produce cloud cover and infrared information over the entire globe.

2 TIROS III before launch. Cameras are centered in the bottom. Solar cells cover the top and all sides. Weight of TIROS III was about 280 pounds.

rockets and balloons, satellites carry instruments far above the layer of air hugging the ground; like big networks of stations, they afford a wide geographical perspective of world weather. In fact, no combination of surface station networks can match the panorama of world weather radioed back from satellite cameras.

The meteorological satellites presently operating do have limitations. They orbit so high up that they cannot make direct measurements of temperature and pressure with ordinary thermometers and barometers. They can only "see" what is going on far below. Seeing alone, however, is of great value to meteorologists. Cloud pictures—the stock-in-trade of the weather satellite—show the great weather systems forming, swirling, and dissolving against the backdrop of the oceans and continents. By taking pictures of the Earth in the infrared portion of the electromagnetic spectrum, weather satellites give the meteorologist information about the heat added to and lost from the Earth and its atmosphere. Since the vast cyclones and anticyclones that roll across the globe are really monstrous heat engines, this heat budget information helps forecast weather. Weather satellites by themselves cannot provide all the information needed for good forecasts, but they can help significantly.

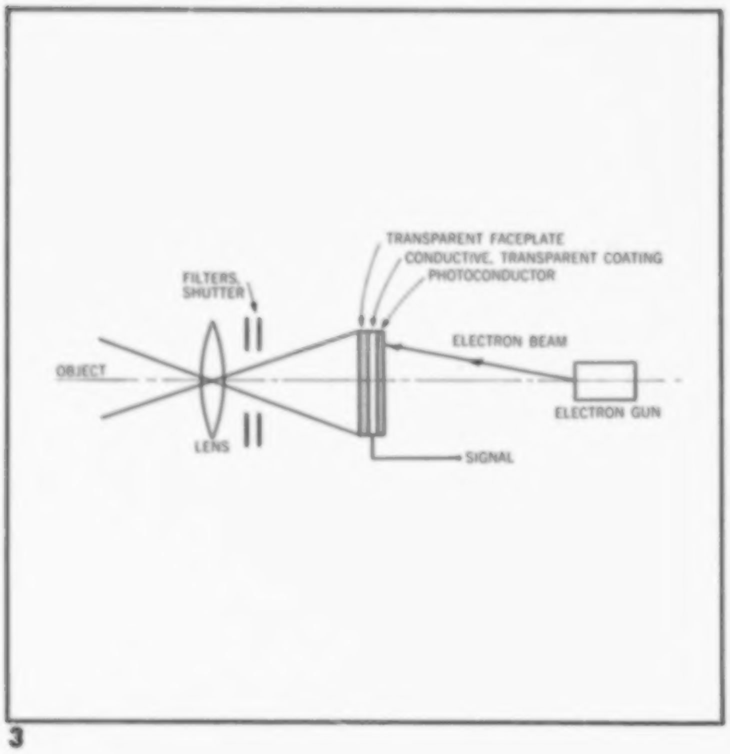


Pictures by the Thousand

Anyone who has flown in an airplane and looked down on the great white cloud banks marching across the landscape has seen only a small fraction of what a satellite sees. An airplane does not fly high enough to see the big picture. Meteorologists did not see truly large-scale pictures of cloud patterns until cameras were flown on high altitude rockets in the late 1940s and early 1950s. What they saw whetted their appetites for more.

The Army, Navy, and industry began studying weather satellites in the early 1950s. In particular, the Radio Corporation of America (RCA) applied to meteorology the experience it had gained studying television-equipped satellites for the Air Force. After it was created in 1958, NASA supported the RCA work. The RCA weather satellite concept eventually became known as TIROS (*Television Infrared Observation Satellites*).

The first TIROS satellites had the proportions of a hatbox, although they were considerably larger: 42 inches in diameter and 22.5 inches high. They weighed about 270 pounds. The top of the hatbox and each of the 18 facets around the circumference were



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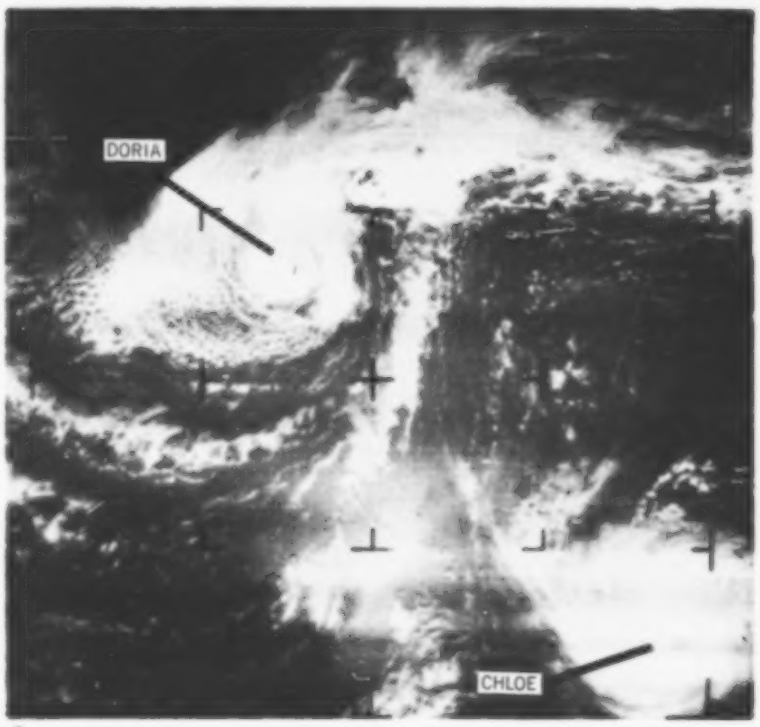

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covered with solar cells, which generated electrical power for the TV camera and the radio transmitter that relayed pictures to antennas waiting on Earth below. The TIROS satellites were spin-stabilized; they spun at about ten revolutions per minute. The satellite's angular momentum kept it from tumbling in space, just as the spin of a rifle bullet stabilizes its flight. On TIROS I, the axis of the hatbox remained approximately fixed in space. As the satellite circled the Earth, its cameras, which were mounted on the bottom of the spacecraft, pointed wherever the satellite axis pointed, which more often than not was toward empty space. Later TIROS satellites carried a coil of wire to improve the cameras' view of the Earth. When electric current was sent through the coil, the satellite became a weak electromagnet and turned in the Earth's magnetic field like the armature of an electric motor. Nevertheless, the early TIROS satellites saw and photographed the Earth only part of the time. A rather frustrating situation, but a complete solution to the problem of camera pointing had to be deferred to the second-generation Nimbus weather satellites.

The heart of a TIROS satellite is its complement of television cameras. Ordinary television cameras, which take many frames a second to give the illusion of smooth motion, cannot be used because TIROS could not possibly transmit that much information to the ground.* A special television tube called a vidicon is used on most U.S. picture-taking spacecraft whether they photograph the Earth's clouds, the lunar surface, or Mars. Replacing conventional film, the vidicon has a sheet of photo-conductive material, which becomes a good conductor of electricity wherever light hits it. Before the shutter of the vidicon is opened to take a picture, the photoconductive sheet is sprayed uniformly with electrons. Then, the shutter is opened and the scene is focused on the sheet. Bright areas in the picture activate the photoconductive material, causing the deposited electrons to be drained away. Electrons remain in the dark areas of the picture. Now an electron gun sweeps across the photoconductive sheet in a pattern or raster consisting of several hundred lines. The electrons from the electron gun will be repelled from dark areas but not from bright areas. The current of electrons flowing out of the electron gun onto the photoconductive surface is thus a

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** The transmission of information requires power; double the number of television frames per minute and the power must be doubled.*

3 *Schematic of a vidicon camera.*

4 *Nimbus II APT photo of two 1967 hurricanes, taken September 13. Hurricane Doria is about 300 miles southeast of Cape Cod and Chloe is roughly 1000 miles southeast of New England. The storms are about 700 miles apart.*

measure of the brightness of the image being scanned. This fluctuating current is turned into a signal that can be converted into a television picture back on the Earth.

Between 1960 and 1965, ten TIROS satellites were launched without a failure. All ten radioed back pictures of the Earth's cloud cover—hundreds of thousands in all. The TIROS pictures presented a grand global panorama of the Earth, grander by far than the sights seen by the first balloonists and aeronauts.

The most striking and exciting features of the TIROS pictures have been the large-scale cloud patterns, which show a degree of organization never realized from terrestrial and aircraft observations. In particular, huge vortices—some 1000 miles across—wheel across the oceans and the continents, making weather as they go.

TIROS photos clearly show weather fronts and other patterns that coincide closely to the maps drawn for the newspapers from accumulated surface station readings. This proven correspondence gives meteorologists confidence that they can employ satellite cloud-cover pictures to draw weather maps in portions of the world where ground weather stations are sparse or nonexistent. The correspondence between the satellite panorama and ground-level direct measurements is not perfect. These discrepancies, though small, have led to modification of cyclone theory.

In the pre-TIROS days, hurricanes used to sweep in from the unpatrolled oceans and slam into land areas with little warning. Destruction and loss of life have frequently been high; much higher than they would have been with ample warning time. TIROS has changed all that by constantly monitoring cloud cover over the desolate reaches of the oceans. Anyone who watches TV news programs during the hurricane season has seen TIROS pictures of these intense storms and followed their progress along the U.S. Atlantic coast. Satellite pictures often catch these storms in their formative stages, showing the prehurricane squall lines that ring the growing nucleus. Sometimes, a hurricane interacts with a jet stream, giving meteorologists a ringside seat for the battle between these two powerful weathermakers. Without the high vantage point of the weather satellite this drama would go unseen.

As the atmosphere swirls across the surface of the Earth, it encounters land formations that deflect the

5 *In a Sun-synchronous orbit, the orbital plane rotates (precesses) about a degree per day to keep the plane of the orbit (shown edgewise) pointed at the Sun. With no perturbing forces, the plane of the orbit would remain fixed in inertial space. Irregularities of the Earth cause the precession.*

6 *TIROS IX, showing the wheel configuration. Satellite spins like a wheel around the Earth, pointing its two cameras (180° apart) at the Earth one after the other.*

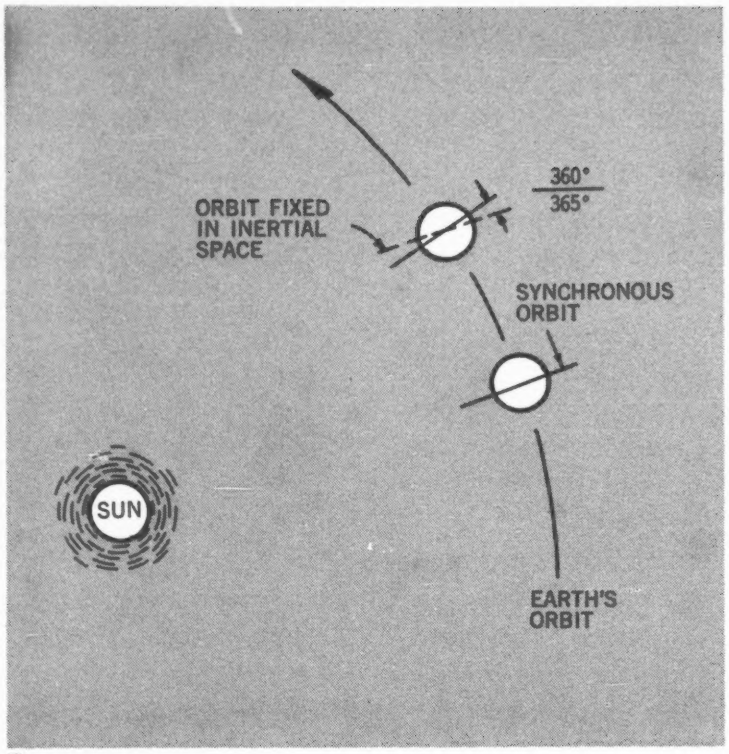
air currents and cause turbulence. The patterns created are intriguing as well as instructive. The Sierra wave, for example, manifests itself as a long linear cloud created as air is pushed up as it tries to slide over the Sierra range. The Andes form similar cloud patterns. In a similar vein, ocean islands with high mountains create strange eddies of clouds that reveal large-scale turbulence, which except for size resembles the turbulence formed behind rocks in a brook.

The first eight TIROS satellites were very much alike. Although they were very successful, NASA and RCA engineers wanted to try some new ideas. TIROS IX introduced the so-called "wheel" configuration in 1965. Instead of mounting the cameras so that they pointed down from the bottom of the hatbox, two were placed on the satellite rim facing outward, 180° apart. After TIROS IX was launched, its axis was twisted so that as it spun it essentially rolled around the Earth, pointing one camera and then the other at the Earth. In the wheel configuration, the TIROS cameras can take more pictures of the Earth.

TIROS X solved another problem: the fact that the angle with which sunlight hits the Earth below the satellite is often poor for picture taking. We cannot control the Sun or the orbit of the Earth, but we can place the satellite in a Sun-synchronous orbit. In this kind of orbit, the satellite is injected into a near-polar orbit. The plane of the satellite orbit contains both the Earth and the Sun. If this configuration could be maintained, the satellite would cross the equator at just about local noon on the sunlit side of the Earth and local midnight on the dark side. The Earth would rotate under the satellite orbit, which is fixed in space, at the rate of 15° per hour. In this way, the equatorial and temperate zones of the Earth could be photographed with the Sun high in the sky all of the time. However, as the Earth rotates around the Sun, it disturbs this ideal situation. The satellite orbital plane remains fixed in space so that a quarter of a year later, it will be perpendicular to the plane containing the Earth and Sun. To maintain the Sun-synchronous condition, the plane of the satellite orbit has to be rotated 360/365 degrees per day. If the satellite is in just the right orbit, the Earth's equatorial bulge will deflect the satellite orbit just this amount. TIROS X demonstrated the practicality of this type of orbit.

While the TIROS program was proving the value of the weather satellite, NASA also worked on the Nimbus weather satellite program. Basically, the Nimbus program is aimed at improving the instruments and spacecraft components used on operational weather satellites.

The Nimbus satellites are large automated spacecraft. For example, Nimbus I weighed 912 pounds, over three times the weight of the early TIROS satellites. Nimbus is fully stabilized; that is, the satellite is oriented so that its instruments always point toward



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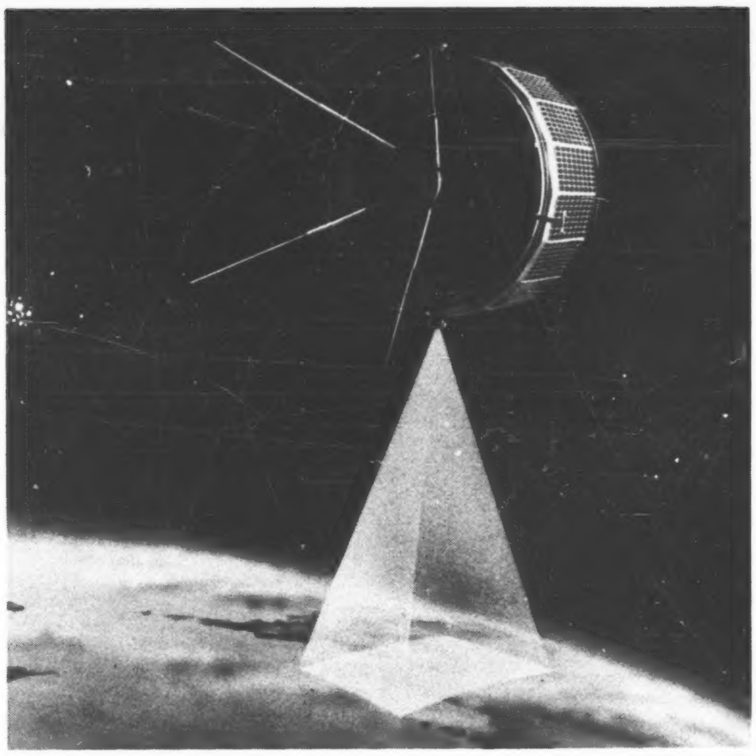

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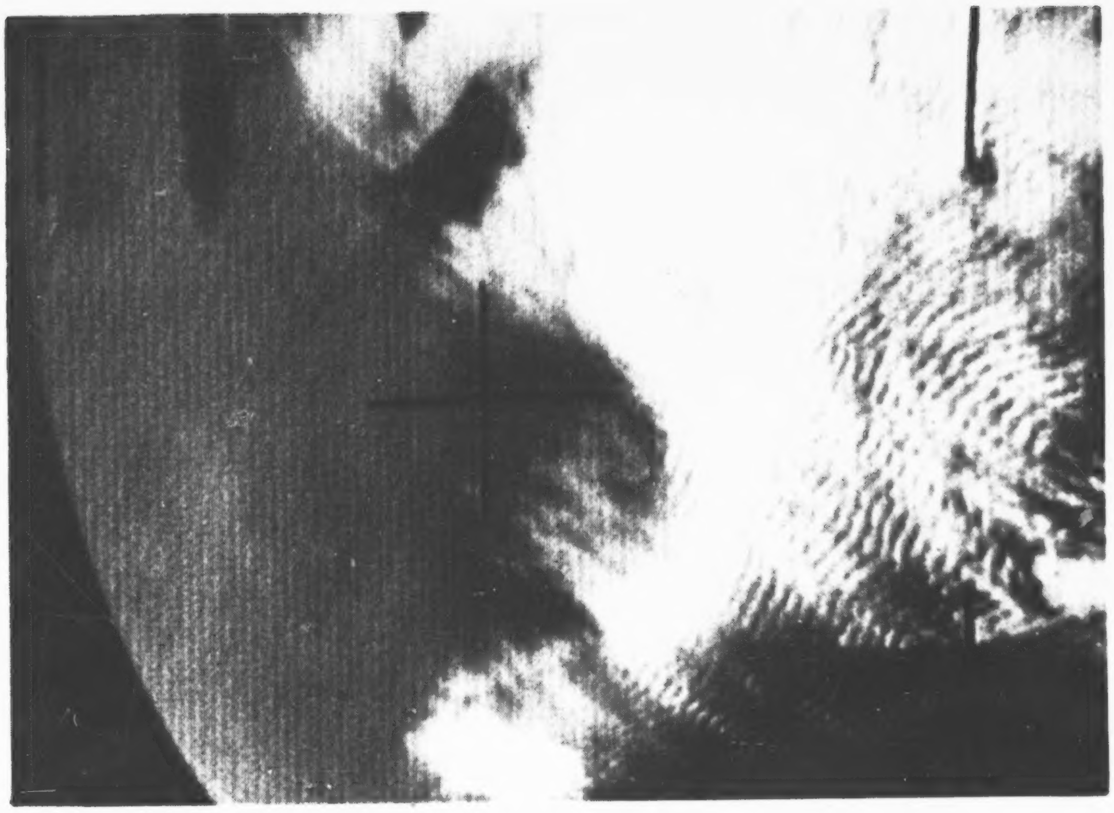
the Earth. The Nimbus attitude control scheme employs three flywheels plus nozzles that squirt Freon gas into space to obtain thrust. Between the flywheels and the jets, the satellite can be kept pointed to within 1° of the center of the Earth's disk.

Nimbus I, launched August 28, 1964, proved the basic spacecraft design, especially the oriented solar panels and the attitude control system. Nimbus I carried three important experiments as well: (1) A new high resolution TV cloud mapping system (the Advanced Vidicon Camera System, or AVCS); (2) An Automatic Picture Transmission (APT) system that allowed local stations to receive weather pictures directly; and (3) A high resolution infrared instrument that allowed nighttime cloud mapping on a global scale. Nimbus II, launched May 15, 1966, carried the same instruments as Nimbus I plus a medium resolution infrared instrument. Future Nimbus satellites will prove out a great variety of optical equipment as well as a nuclear power supply for augmenting the solar panels.

The wheel configuration of TIROS IX, the Sun-synchronized orbit of TIROS X, and the Nimbus camera technology were adopted by the U.S. Weather Bureau for its TIROS Operational Satellites (TOS). The Weather Bureau is now part of the Environmental Science Services Administration. Its satellites are called ESSAs, for Environmental Survey Satellites. Three ESSAs were launched by NASA for the Weather Bureau in 1966 and two more in 1967. The successes of the TIROS and Nimbus programs can be gaged by the adoption of their technologies for operational, routine weather satellites.

Hot Spots Below

Each hurricane is created and sustained by a colossal heat engine that we are just beginning to understand. Somehow, energy from the Sun starts these atmospheric machines turning over. The same is true for the much bigger, but less intense cyclones and anticyclones that make most of our weather. Since weather is really atmospheric turbulence created by too much solar heat at the equator and too little at the poles, measurements of the Earth's heat inflow and outflow should be useful to meteorologists. For this reason, most NASA weather satellites have carried infrared radiometers to record the thermal radiation emitted from the cloud tops and the visible land surface below the satellite. The thermal radiation emitted by the Earth falls mainly in the



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7 *Wave clouds over the Appalachian Mountains, photographed by TIROS VII.*

8 *The Nimbus weather satellite carries attitude control devices (gyros and gas nozzles) that keep its cameras in the base pointed at the Earth. The solar cell paddles are driven by a motor that keeps them perpendicular to the Sun's rays.*

range from 5 to 50 microns.* These wavelengths are far longer than the long wavelength limit of the eye at about 0.7 micron. Unlike the vidicons which operate with visible light, the infrared radiometers are useful both day and night in determining cloud cover and the speed with which the Earth cools once the Sun has set.

In infrared radiometers, lenses focus the infrared radiation on a detector made from a photoconducting material, such as lead selenide, which becomes a good electrical conductor when illuminated by infrared light. The amount of current passed by the detector is proportional to the intensity of the infrared light and therefore the amount of heat being radiated from Earth to outer space.

Infrared radiometers can be made sensitive to various wavelength ranges or channels through the use of filters. For example, the high resolution infrared radiometer on Nimbus I was sensitive to only that radiation between 3.4 and 4.2 microns. Radiation of this wavelength is emitted from cloud tops and gave Nimbus I a way of mapping cloud cover at night. An infrared channel between 6 and 7 microns helps determine the amount of absorption caused by water vapor in the air. Data from such a channel aid in constructing worldwide humidity charts of the upper atmosphere. Analysis of the radiation emitted by the

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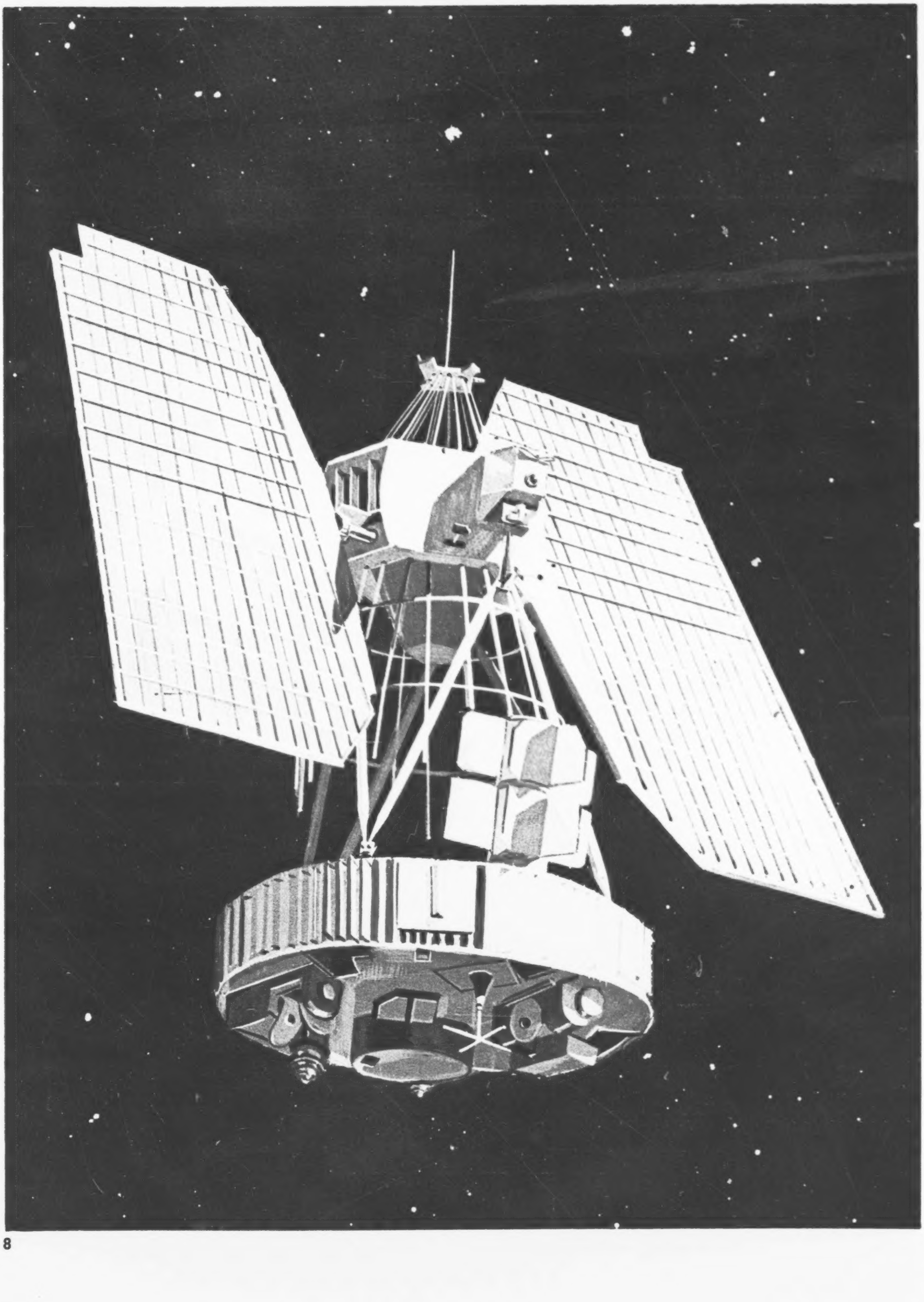
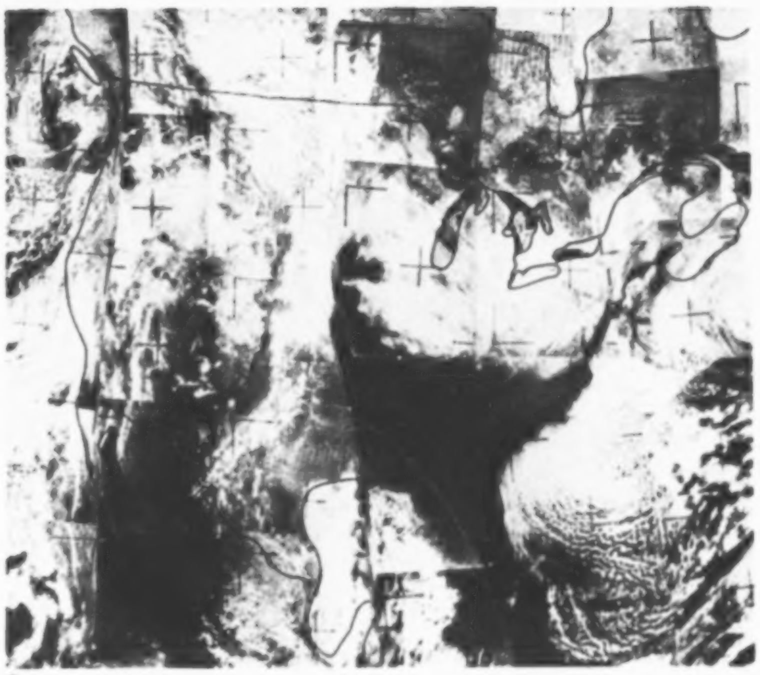
* *A micron is one-millionth of a meter.*





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9 *ESSA I took this picture of North America on February 5, 1966. It shows a heavy rain producing storm along the west coast, ice in Lake Erie, snow cover over Northeastern United States, clouds in cold air flow off the east coast.*

10 *The High Resolution Infrared Radiometer on Nimbus II was able to distinguish the Gulf Stream along the U.S. east coast by virtue of its warmer temperature.*

warm Earth by radiometers, spectrometers, and other optical equipment can provide the following kinds of meteorologically useful data:

Atmospheric temperature and humidity profiles
Vertical water vapor distribution
Vertical ozone distribution
Surface temperature

When added to photos taken in visible light by weather satellite cameras, meteorologists see the world's weather from a superb vantage point at wavelengths they have never been able to use before.

Pictures on Request

Will the Boy Scout hike be rained out tomorrow? Do the smudge pots have to be lit in the orange groves tonight? This is the kind of weather information that most people want to know; that is the local forecast, the local situation. The local weather forecaster would like very much to see what is going on in his area as he prepares his predictions. The APT (Automatic Picture Transmission) system gives him local cloud pictures with a minimum investment in equipment.

The basic idea is to have special cameras on the weather satellites (TIROS, Nimbus, ESSA) that continually transmit cloud cover pictures as they are taken. Anyone on the Earth below within 1500 miles of an APT-equipped satellite can receive these pictures with modest equipment that he can purchase or build himself. Every time an APT satellite passes overhead, the owner of an APT ground station can collect up to three overlapping pictures of weather systems within about 1000 miles of his station.

The APT concept is particularly helpful to foreign weather forecasters who cannot get the maps and cloud cover photos that the U.S. Weather Bureau transmits to many U.S. locations. Hundreds of APT ground stations have been set up all over the world, not only by professional weathermen but also by radio amateurs and high school science classes.

Extraterrestrial Relays

The Advantages of Height

More and more TV programs come to us from the far corners of the world *via satellite,* as the subtitles sometimes say. What is not

GULF
STREAM
BOUNDARY

10

so obvious is the immense commercial and military communication traffic carried between continents by satellite. Not only do people talk to people, but computers and data handling equipment talk among themselves in their own languages.

The possibility for this global conviviality was first described back in 1945, when the British writer Arthur C. Clarke, better known for his science fiction, published an article entitled "Extraterrestrial Relays" in the magazine *Wireless World.* Clarke pointed out that small artificial satellites in orbit high above the Earth could relay messages between continents and greatly improve long distance communication. As befits a writer of science fiction, Clarke was ahead of his time, but only by about fifteen years.

Radio waves travel away from their transmitting antennas in straight lines at the speed of light. Unless something changes their direction of travel, radio communication beyond line of sight is impossible. The Earth's ionosphere some fifty miles above the surface reflects some radio waves back to Earth, making long distance communication possible. But the ionosphere is fickle, moving up and down and disappearing when we don't want it to. Further, it reflects only those wavelengths longer than roughly 100 feet.* Dependable, long range radio communication requires an artificial radio wave reflector high in the sky.

Covering the whole sky with radio wave reflectors is out of the question; but, as Clarke suggested, satellites can do the job. The most primitive kind of communication satellite is passive in character; that is, it only reflects the signals hitting it, like a mirror. In contrast, active communication satellites rebroadcast signals with greater strength. Signal amplification takes electrical power, of course, but the relayed signals are easier to detect.

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* *Equivalently, frequencies below 10 MHz (10,000,000 cycles per second) are reflected.*

11 *Echo I, a 100-ft diameter balloon satellite. Echo I was a passive communication satellite.*

12 *NASA has experimented with passive and active communication satellites at various altitudes. The active synchronous satellite was ultimately selected for commerical use.*

11

Height above the Earth's surface makes communication satellites useful. Antennas well over the horizon at ground level can see a satellite in a 100-mile orbit. A communication satellite in a synchronous orbit 22,300 miles high can be seen by nearly half the radio antennas on Earth. A system of three or more evenly spaced synchronous communication satellites can relay messages between any two points on the inhabited parts of the globe.

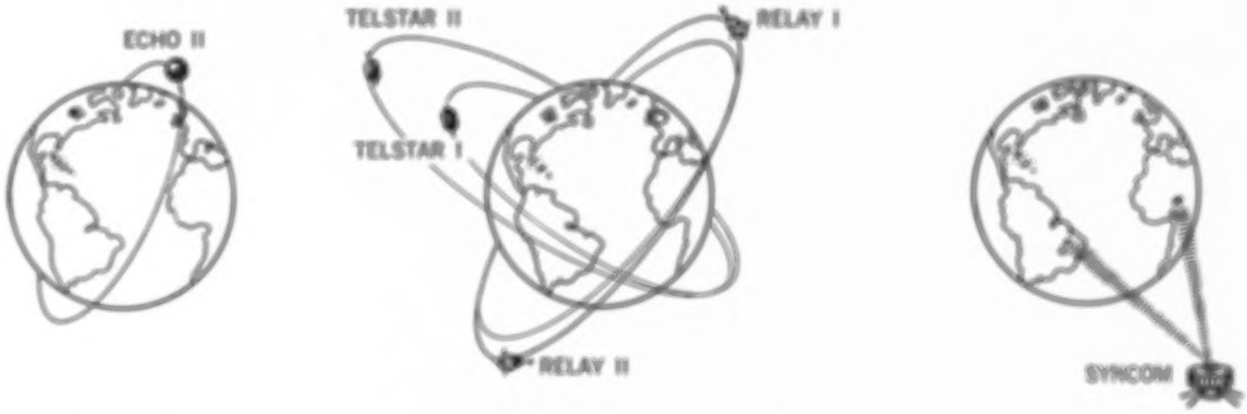
Balloons in Orbit

One prominent communication satellite is rarely mentioned: our natural satellite, the Moon. During the 1950s, the U.S. Army bounced radio signals off the Moon in long range communication experiments. And while artificial satellites were getting all the glory, the Moon gave the Army an operating communication link between Washington and Hawaii. This was the world's first operational space communication system; it was called CMR, for Communication by Moon Relay.

Would an artificial moon be any better than the natural one? It would certainly be much closer, reflected signals would be much stronger, and signal delay times would be negligible compared to the 2½ seconds for Moon bounces. To test the artificial moon idea, NASA launched two metalized plastic balloons that inflated once in orbit. Echo I (100 feet in diameter) was launched in 1960; Echo II (135 feet in diameter) in 1964.

By aiming transmitting and receiving antennas at the balloons, two-way conversations between the U.S. and Europe proved feasible. There was no limit to the number of users. This multiple access feature is one of the big advantages of the passive communication satellite. Other pluses are their long life and high reliability. With no parts to fail or wear out, balloon satellites should last forever. They don't; they get punctured by meteoroids; they get wrinkled and eventually the tiny bit of atmosphere remaining will slow them down and bring them back to Earth. This is just what happened to Echo I on May 23, 1968 when it reentered the atmosphere and burned up over South America.

Despite all their virtues, passive communication satellites were bypassed in favor of active repeaters. One reason is that a great many balloons—perhaps 50—would have to be launched into low orbits to make worldwide communication possible. Orbits had to be low because signals reflected from high altitude



PASSIVE

- Long life
- Multiple Access

- Large Antennas
- Large Transmitters
- Low Altitudes
- Large Numbers
- Capacity Low

ACTIVE (LOW & MED. ALTITUDES)

Active (Low & Med. Altitudes)
- Simplest Active
- Capacity High

- Ground Station Complexity
- Large Numbers (Multiple Launch)
- Traffic Management Complex

ACTIVE (SYNCHRONOUS)

Active (Synchronous)
- Small Numbers
- Simple Ground Stations
- Capacity High
- Traffic Management Simpler

- Complex Spacecraft
- Station Keeping
- Complex Launch

12

satellites would be too weak. Because the balloon satellites do not amplify the signals, ground stations have to have big antennas and high power transmitters.

Active Communication Satellites

The U.S. Army in its perpetual search for more reliable and more secure long-distance communications built the first active communication satellite. SCORE (an acronym for Signal Communication by Orbiting Relay Equipment) was launched on December 18, 1958. SCORE relayed voice conversations, code, and teletype directly. The satellite also carried a tape recorder that stored messages and repeated them when triggered by a signal from the ground. President Eisenhower's 1958 Christmas message was carried around the world by SCORE in one of its more dramatic performances. Score ceased operation after twelve days.

The Army followed up its success with SCORE by orbiting Courier in 1960. Courier was a large satellite by U.S. standards; it weighed 500 pounds. It was covered with 20,000 solar cells, and carried four receivers, four transmitters, and five tape recorders. During its 18 days of active life, Courier received and retransmitted 118 million words.

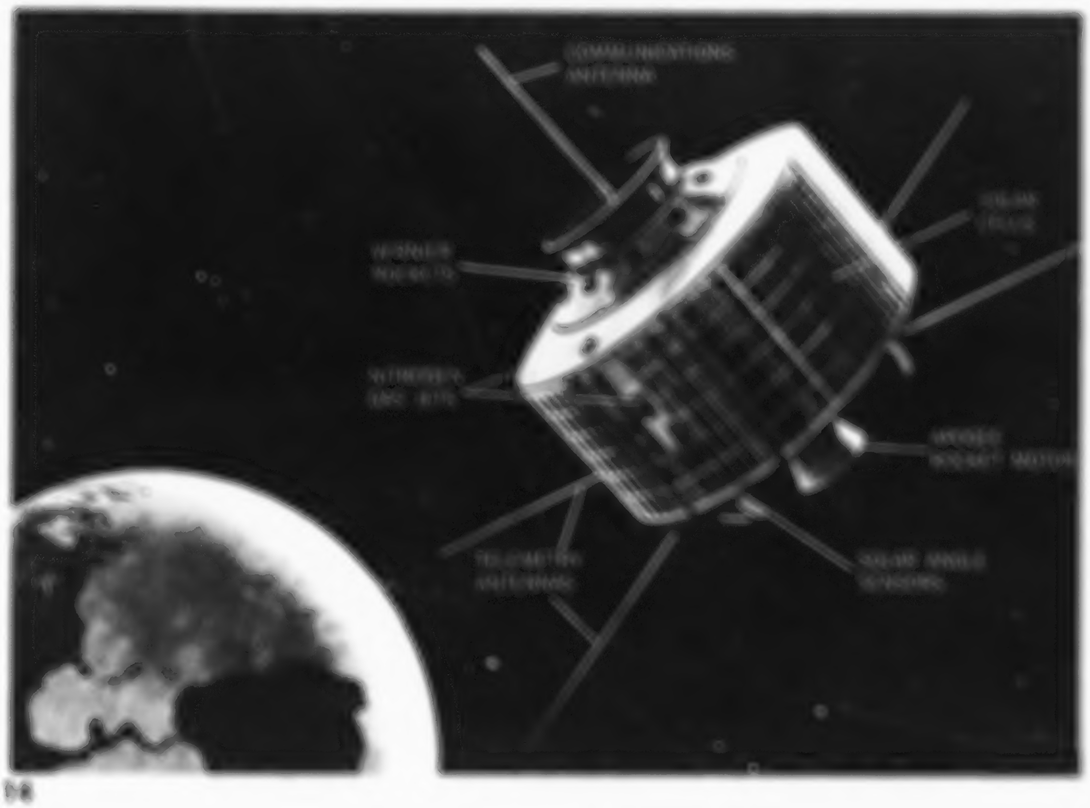
Despite these successful demonstrations, the commercial feasibility of the communication satellite was unproven. How long could an active communication satellite operate? Should it be at high, low, or intermediate altitude? How many should there be? Three programs were designed to answer questions like these: the NASA Relay and Syncom programs and the joint NASA-AT&T Telstar program.

The Relays were medium altitude (about 4600 miles) active repeaters; while the Syncoms were injected into synchronous orbits at about 22,300 miles. The two Telstars were designed by AT&T, with NASA providing the launching rocket and the ground tracking facilities on a reimbursable basis. They were placed in orbits similar to those of the Relays. The Telstars foreshadowed the fact that the success of communication satellites would inevitably bring private industry into the picture.

When an engineer tries to answer a complex question like: What kind of communication satellite is best? he thinks in terms of tradeoffs. He can, for example, put his satellite in a higher orbit to gain a better view of the Earth's surface in trade for a loss in signal strength from the more distant satellite. Or, he can add more solar cells to the satellite to increase transmitter power at the expense of discarding one of the extra transmitters he wanted to make the

13 *A communication satellite ground terminal at Andover, Maine. The antenna consists of a large horn that collects the incoming radio waves. This facility belongs to the Bell Laboratories.*

14 *Artist's concept of the Syncom satellite.*



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satellite more reliable. What the engineer wants to do is optimize the entire communication system from ground station to satellite to ground station. Because communication is a salable commodity, optimization usually means transmitting the most information for the least cost in terms of satellites, ground facilities, and operations.

The question of communication satellite altitude provoked the biggest battles among the engineers. The altitude options were three: low (100 to 500 miles); medium (2000 to 12,000 miles); and synchronous (22,300 miles). Altitude buys visibility. Also, the higher the satellite the more slowly it moves from horizon to horizon and the easier it is to follow with antennas. The visibility of low orbit satellites was so poor that fifty to one hundred would be required for good worldwide coverage. Further, they would fly over so quickly that ground station operators would have to pick up a new satellite every few minutes. For these reasons, low altitude communication satellites were eliminated from the competition early.

By this reasoning, the synchronous satellites should have been adopted forthwith. With three synchronous satellites spaced equally around the equator, almost every inhabited spot on Earth would be covered. Ground station antennas could be aimed at the satellite and locked into position because synchronous satellites over the equator rotate at the same speed as the Earth and would appear to be fixed in space. Actually, the synchronous solution was not obvious because high altitude is good for some things but bad for others. To illustrate:

1. The launching and positioning of a synchronous satellite is difficult. The altitude has to be just right. To launch an equatorial satellite from Cape Kennedy, the launch rocket trajectory has to take the satellite south and then turn ("dogleg") when over the equator and inject the satellite into orbit.
2. Furthermore, once the tough synchronous equatorial orbit has been achieved, the satellite has to run continually just to stay in one place—

U. S. COMMUNICATION SATELLITES

Satellite	Launch Date	Injected Weight (lbs)	Orbit (miles)		Remarks
			Apogee	Perigee	
SCORE	12-18-58	8750[1]	914	115	First active comsat. Transmitted for 13 days.
Echo I	8-12-60	166	1052	941	First passive comsat. Relayed voice and TV.
Courier 1B	10- 4-60	500	767	586	Functioned 17 days. Active.
Telstar 1	7-10-62	170	3053	593	Medium altitude active comsat.
Relay I	12-13-62	172	4612	819	Medium altitude active comsat.
Telstar 2	5- 7-63	175	6713	604	Medium altitude active comsat.
Syncom I	2-14-63	86	22953	21195	In near-synchronous orbit. Communications lost at injection.
Syncom II	7-26-63	86	22750	22062	First successful synchronous comsat.
Relay II	1-21-64	172	4606	1298	Medium altitude active comsat.
Echo II	1-25-64	547	816	642	Passive comsat.
Syncom III	8-19-64	86	22312	22164	First Geo-stationary comsat.
LES 1[2]	2-11-65	545	393	343	Air Force all-solid-state comsat.
INTELSAT I[3] (Early Bird)	4- 6-65	85	22733	21740	Owned by INTELSAT Corp.[3] ? Consortium Based on Syncom technology.
LES 2	5- 6-65	82	9384	1757	Air Force comsat.
LES 3	12-21-65	35	18000	100	Air Force comsat.
LES 4	12-21-65	115	20890	124	Air Force comsat.
IDCSP 1-7[4]	6-16-66	100	all near-synchronous		Seven Air Force comsats launched together.
INTELSAT II F-1	10-26-66	190	23300	2020	Not in planned synchronous orbit.
INTELSAT II F-2 (Pacific 1)	1-11-67	192	22257	22254	For transpacific commercial service.
IDCSP 8-15	1-18-67	100	all near-synchronous		Eight Air Force comsats launched together.
INTELSAT II F-3 (Atlantic 2)	3-22-67	192	22254	22246	
IDCSP 16-18	7- 1-67	100	all near-synchronous		Eight Air Force comsats launched together.
INTELSAT II F-4 (Pacific 2)	9-27-67	192	22245	22220	
IDCSP 19-24	6-13-68	100	all near-synchronous		Eight Air Force comsats launched together.

[1] *Includes last stage of launch vehicle.*
[2] *LES = Lincoln Experimental Satellite, built by Lincoln Laboratory.*
[3] *INTELSAT = International Telecommunications Satellite Consortium, an organization of more than 60 countries; also INTELSAT spacecraft.*
[4] *IDCSP = Initial Defense Communication Satellite Program.*

just like Alice in Wonderland. Natural forces, such as the pressure of sunlight and the gravitational attraction of the Sun and the Moon, keep pushing the satellite from its assigned position. Keeping it in the same spot is called station keeping, and it is accomplished by small nozzles that squirt charges of cold gas whenever the orbit needs correcting.

3. Synchronous communication satellites are smaller than medium orbit communication satellites

because rocket payload is sacrificed to reach the higher altitude and perform the dogleg maneuver.

4. Signals relayed from 22,300 miles are some twenty times weaker than those from 4,000 miles, assuming the same transmitter power levels. In addition, there are significant propagation delays resulting from the fact that radio waves do not travel infinitely fast.

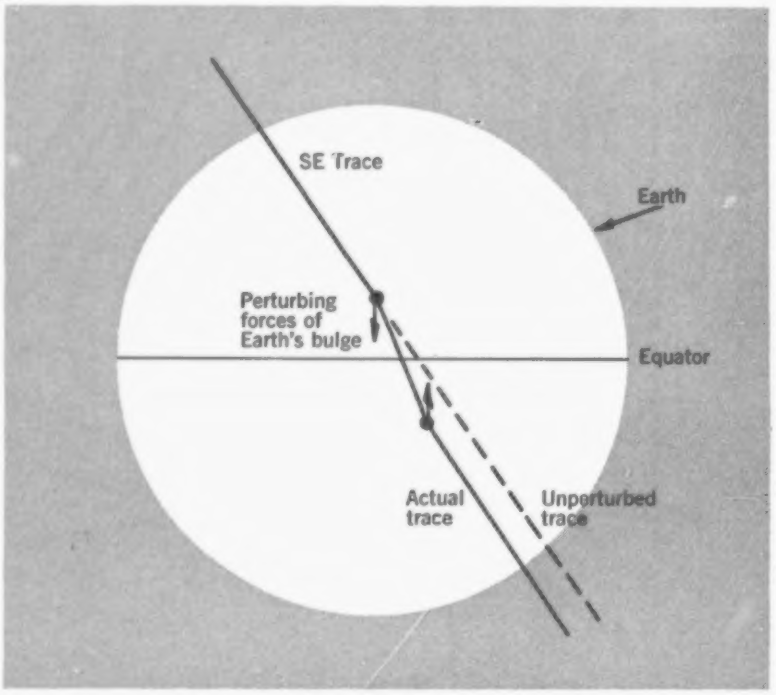
Despite these objections, synchronous communication satellites finally emerged victorious. The last half of the following table attests to the completeness of this victory. The NASA Syncoms paved the way by proving that synchronous orbits could be attained and maintained on an operational basis. Without this practical proof of feasibility, the debate might still be going on.

Once NASA proved the feasibility of the synchronous communication satellite, the technology was used by a commercial enterprise called the Communications Satellite Corporation—Comsat for short. Comsat was created by an act of Congress on August 31, 1962. It was formally incorporated on February 1, 1963. The large communication companies and the public hold stock in the Corporation, which is closely regulated by the Government.

Comsat's two major tasks were to establish an operational system of communication satellites and enlist the support of foreign governments in setting up international service. The Early Bird satellite, launched in 1965, was similar to the NASA Syncoms. By the time Early Bird was in orbit, about thirty countries were participating. More satellites were launched and more countries joined the effort. Regular transoceanic service commenced in 1967 as Comsat stationed synchronous communication satellites over the Atlantic and Pacific oceans.

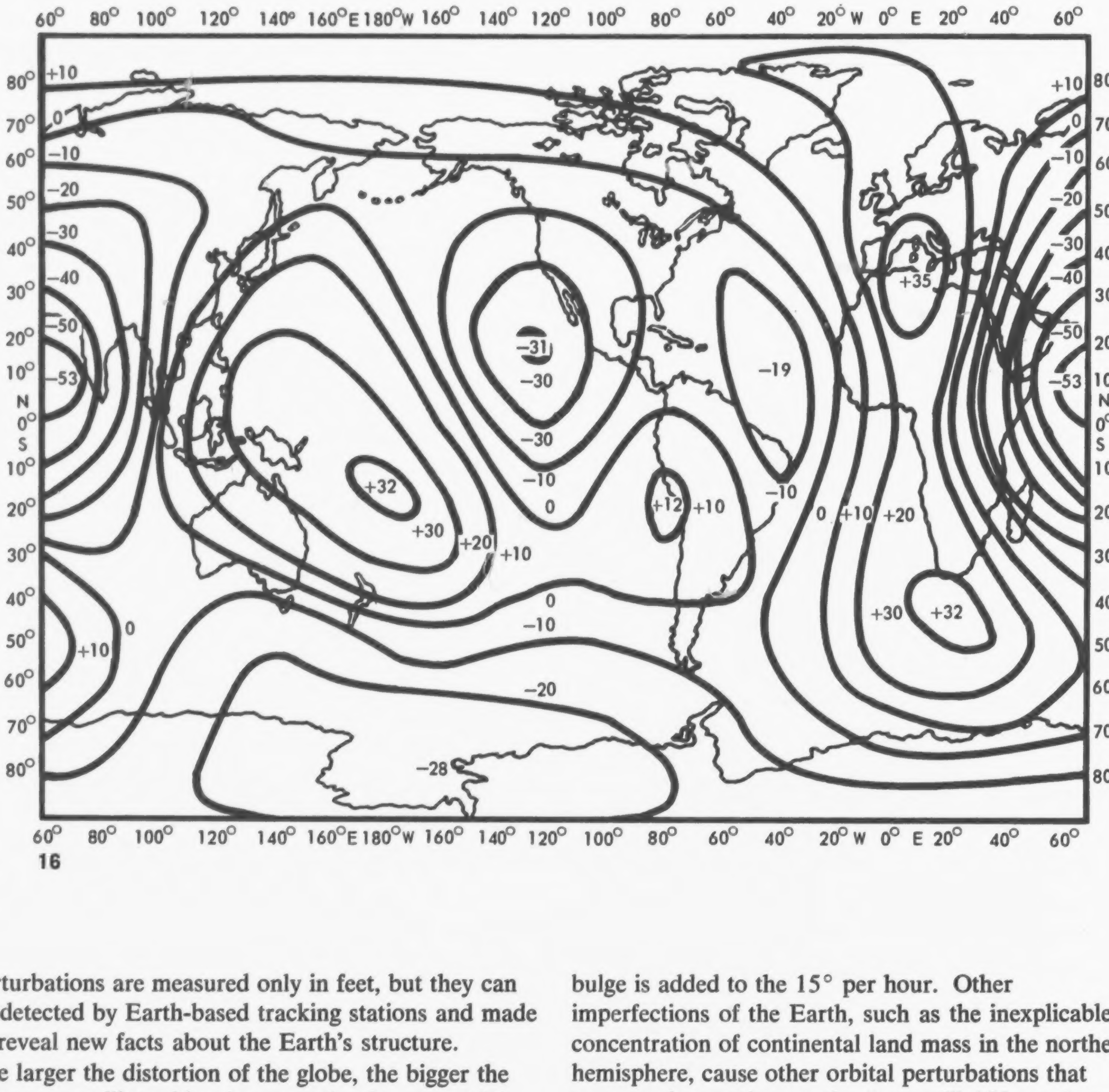
The Figure Of the Earth

Satellites have once more proved that the Earth is round, but how round is it? Answering this question is the first task of *geodesy,* the science that deals with the shape or "figure" of the Earth and the nuances of its gravitational field. The Earth's field is far from uniform. Large sections of the Earth's crust have different densities; heavier sections locally strengthen the Earth's field, lighter sections weaken it. Such differences in the gravitational field are termed "anomalies," and many are detectable by satellites. For decades, small-scale anomalies have guided geologists to local mineral deposits. Eventually satellites may be able to do the same. In addition to describing the shape of the Earth and the structure of its field, geodesy is concerned with accurately locating points on the Earth's surface with respect to one another. The precise whereabouts of points on the Earth is basic to map makers, navigators on ships and planes, and NASA itself, which must know exactly where its spacecraft tracking stations are located.



15 *The gravitational pull of the Earth's bulge deflects a satellite slightly westward each pass.*

The orbital path of a satellite is not a perfect ellipse. The satellite weaves sideways and up and down as it plies its course around the Earth. These small orbital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16

perturbations are measured only in feet, but they can be detected by Earth-based tracking stations and made to reveal new facts about the Earth's structure. The larger the distortion of the globe, the bigger the effect on satellite orbits; for example, the equatorial bulge of the Earth causes the entire plane of the satellite orbit to rotate in space.

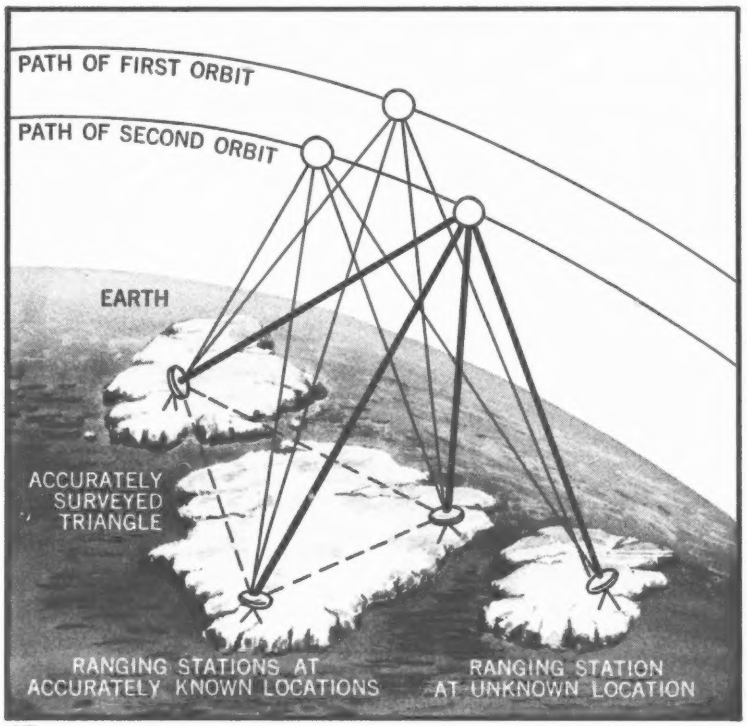
The bulge perturbation can be understood by considering a satellite approaching the equator from the northwest. The extra mass in the bulge gives it an extra southward pull. This deflects the satellite orbit into a more southerly path. After it passes over the equator, the bulge pulls the satellite north and straightens the orbit out. But it is too late, the plane of the orbit has already been shifted westward. To a ground observer the plane of a satellite's orbit seems to shift westward 15° each hour, as the Earth rotates under the orbit. The effect of the Earth's bulge is added to the 15° per hour. Other imperfections of the Earth, such as the inexplicable concentration of continental land mass in the northern hemisphere, cause other orbital perturbations that are superimposed upon the "normal" 15° per hour westward drift.

A geodesist needs extremely accurate ground-based tracking equipment that tells him where a satellite is at every moment. Tracking data will show perturbations from the ideal mathematical ellipse. From the total perturbation, he must subtract those deviations due to the pressure of sunlight on the satellite, the drag of the tiny amount of air remaining at satellite altitudes, and the gravitational attractions of the Sun and Moon. The remaining perturbations should be due to the Earth itself.

For high precision satellite tracking, NASA takes

16 *Map of the Earth's major gravitational anomalies expressed in terms of height above (+) or depression below (—) an ideal Earth shaped like an oblate spheroid. Contours are in meters.*

17 *In the Secor approach to tying geodetic grids together, known and unknown stations observe range of the same satellite simultaneously. The satellite is, in effect, a known landmark.*


PATH OF FIRST ORBIT
PATH OF SECOND ORBIT
EARTH
ACCURATELY SURVEYED TRIANGLE
RANGING STATIONS AT ACCURATELY KNOWN LOCATIONS
RANGING STATION AT UNKNOWN LOCATION

17

photographs of the satellite against the accurately known background of fixed stars with large Baker-Nunn cameras, operated by the Smithsonian Astrophysical Observatory. Localized perturbations to a satellite's orbit can often be measured better with radar or other radio equipment. For example, NASA has experimented with tracking satellites by laser. Explorers XXII, XXVII, and XXIX carried special reflectors that mirrored laser light flashes, permitting accurate range determinations. Eventually, lasers and high precision microwave equipment may be able to fix a satellite's position to within a foot or so.

Precision in satellite tracking leads to precision in terrestrial map making. On the North American continent, surveyors have laid out a grid enabling them to locate any point with respect to another to within about 30 feet. There are similar grids in other well-developed countries, but they are not tied together. A surveyor cannot see over the ocean with his transit to make the connections. The locations of many islands in the Pacific were not known to better than a few miles before satellites were developed. Again, it is satellite height that makes it a valuable tool. Observers several thousands miles apart can see a high satellite simultaneously. By making simultaneous measurements with optical and radio tracking instruments, they can determine just how far apart they really are. The current goal of satellite geodesy is to tie all geodetic grids together with an accuracy of 30 feet. The U.S. Army is expected to make important progress along this line with its Secor (Sequential Collation of Range) satellites. By island hopping across the oceans, using high satellites as geodetic markers, the world's continents will eventually be tied together to one common reference system.

Almost all satellites are valuable to geodesy. The most useful ones are those that are easy to track. The Echo communication satellites, for example, were very useful because they were so easy to see with optical instruments. Pageos is another balloon satellite orbited by NASA in 1966 specifically to help the geodesists. To help make truly simultaneous observations, flashing lights were installed on several "active" geodetic satellites. The lights flash in coded sequences so that widely separated ground stations can compare time exposure photographs taken against the background of the fixed stars. The Department of Defense satellite Anna 1B* carried the first optical beacon into orbit in 1962. Geos I (Explorer XXIX), launched November 6, 1965 by NASA also included a flashing light in its payload. Radio beacons of various types are placed on many satellites to aid tracking. NASA's two Beacon Explorers (Explorers XXII and XXVII) carried both radio beacons and laser reflectors. GEOS II (Explorer XXXVI), launched on January 11, 1968, is now fully operational. In addition to a full complement of geodetic instrumentation, it has C-band radar transponders to determine if the approximately 65 C-band radar tracking stations can track with geodetic accuracy. The preliminary results are far better than were expected.

The United States has centralized its satellite geodetic activities in the National Geodetic Satellite Program. NASA has overall responsibility, and the Departments of Defense and Commerce participate.

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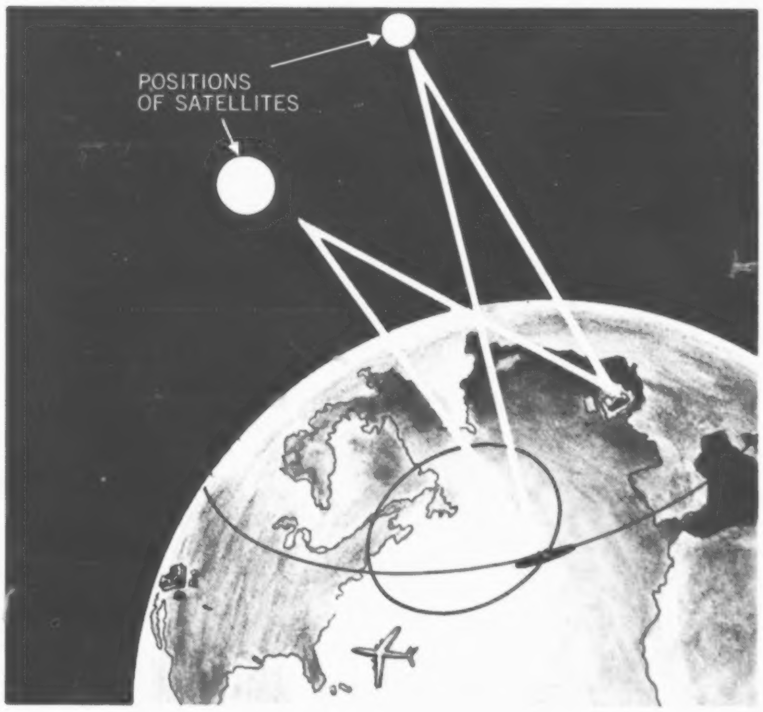
* *Anna = Army, Navy, NASA, Air Force; the cooperating Agencies.*

Better Brick Moons

About a century ago, Edward Everett Hale wrote a short story entitled "The Brick Moon." In it, the hero proposed launching four satellites, 200 feet in diameter, into polar orbits passing over Greenwich, England, and New Orleans. The rockets of the 1870s could scarcely lift Hale's brick moons, so he hit upon the idea of flinging them into orbit with huge flywheels. Once the artificial moons were in orbit, navigators at sea could determine their longitudes by measuring the elevation of the moons above the horizon. It was a precocious plan, although Hale overlooked the fact that satellites cannot remain in orbit over a given meridian because of the Earth's rotation.

Today we need better brick moons to help aircraft and ships fix their positions to within a mile or two. Aircraft traffic is congested and safe control of this

18 *Navigators on the Earth's surface can locate themselves by measuring the ranges of two satellites in synchronous equatorial orbits. The navigator must be at one of the two intersections of the circles.*



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traffic depends upon pilots and traffic controllers knowing precisely where aircraft are located.

The U.S. Navy has already launched its system of navigation satellites: the Transit satellites. The Transit system is complex and expensive; too much so for commercial aircraft and ships. Nevertheless, its features are interesting because they offer ideas for economically practical systems.

A ground rule that makes the Transit system expensive is that a ship trying to fix its position should not transmit signals that would reveal its location to others. With this in mind, the satellite does two things for the ship navigator below:
(1) It transmits a radio signal at constant frequency so that the navigator can obtain a Doppler curve* and (2) It transmits in code the latest information about its own orbit. This information was inserted in the satellite's memory when it last passed over a Transit ground station. From (1), a shipboard computer calculates the satellite's distance of closest approach. Knowing this distance, the orbital data relayed by the satellite, the time, and the ship's speed, the computer gives the navigator his position to within one mile.

A less expensive plan of possible commercial interest would place satellites in stationary orbits above the equator where their positions would be relatively fixed and where they could be seen by most potential users. A navigator wishing to fix his position addresses satellite #1 by radio in a known code. Satellite #1 responds. By timing the transit of signals, the range of satellite #1 can be determined. Next, satellite #2 is addressed, and its range is found in the same way. If the navigator is on a surface vessel, he can now draw two circles on his map. Each circle is the locus of points at the just-measured range from the satellite. The ship is at one or the other of the two points where the circles intersect. Normally, the navigator can resolve this ambiguity from the knowledge that he is at sea rather than in the cornfields of Iowa. An airplane navigator, of course, needs his altimeter reading before he can draw his circles.

Another navigation scheme under study by NASA involves more difficult geometry. Imagine three satellites in stationary orbits over the equator. Satellite #1 (the *master* satellite) emits a radio signal. At two different, precisely known intervals afterwards, satellites #2 and #3 (the *slave* satellites) emit their signals. The signal cycle repeats, and the navigator receives sequences of three signals. Each signal contains information identifying the satellite that originated it. The true time intervals between signals from satellites #1 and #2, #1 and #3, and #2 and #3 are known, but the navigator will receive them at slightly

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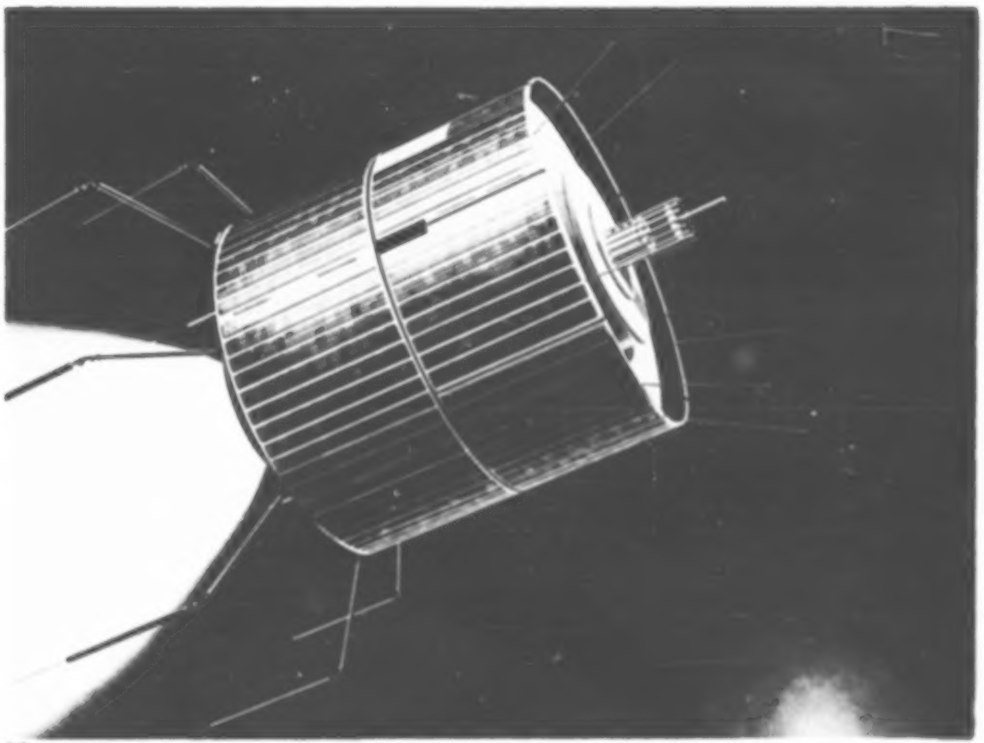
** A Doppler curve is a graph of the apparent frequency of the satellite transmitter. The frequency is higher when the satellite is approaching, lower when receding (like a train whistle).*

19 *ATS I carried a wide variety of weather, communication, and attitude control experiments.*

20 *THE ATS-I view of the Pacific basin from synchronous orbit (about 22,000 miles altitude.)*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different intervals because of the different times required for the radio waves to flash from the satellites to the ship. Knowing these time discrepancies, he can calculate the *differences* between the distances of the three possible pairs of satellites from his ship. The locus of points which have a constant difference in distance from a pair of satellites is a hyperboloid. There is a hyperboloid for each of the three satellite-pair combinations. The navigator finds his position from the common intersection of all three hyperboloids. Though this approach sounds complex, it is really only an extension of a two-dimensional system used for ship navigation since World War II. This system is called loran (Long Range Aid to Navigation). There are many land-based loran master-slave transmitters in the better developed parts of the world. The proposed satellite navigation system extends the loran concept to three dimensions and, in the process, the rest of the world.

Testing Laboratory In Space

Once NASA has developed weather and communication satellites, the responsibility for operating them on a regular basis falls to other agencies of the Government or to private industry. However, NASA retains the job of finding better ways to do these tasks. Better cameras, better means for maintaining stationary orbits, better navigation transponders; all are typical of the new technology NASA is developing.

It often happens that the best way to test a new

20

camera or any other piece of space hardware is to put it on a satellite and try it out. NASA has built a series of Applications Technology Satellites (ATS) for this purpose. The ATS satellites are multipurpose testbeds.

ATS I, the first in the series, looks like a large version of the Syncom communication satellite. It was launched on December 6, 1966 and successfully maneuvered into a synchronous equatorial (stationary) orbit over Christmas Island in the Pacific. The most dramatic results have been the remarkably sharp pictures of the entire Earth. From 22,300 miles up, the ATS special spin-scan camera has been able to take thousands of pictures of planet-wide circulation patterns in the atmosphere. Because the ATS I is fixed in one spot over the Earth, it has been able to provide long sequences of snapshots of weather showing the time development of convection cells, typhoons, and jet streams. In effect, ATS takes a movie of the weather over nearly 40% of the Earth, a perspective the lower, fast-moving TIROS satellites cannot see.

ATS I is also involved with the Weather Data Relay Experiment, more commonly known as WEFAX. The WEFAX experiment has demonstrated the feasibility of disseminating weather data from a central facility to widely scattered weather stations via a synchronous satellite relay. In other words, ATS I acts like a Syncom to relay weather satellite data.

Many communication experiments have also been conducted using the special radio equipment installed on ATS I. ATS I was the first satellite permitting two-way very high frequency (VHF) communication between aircraft and the ground—an important accomplishment for traffic control over the oceans and sparsely populated areas.

The payload of ATS II, launched April 5, 1967, also contained a wide variety of experiments and equipment. The primary objective was to test a gravity-gradient attitude control device. Also included were two weather cameras, a microwave communication experiment, and eight scientific experiments. Unfortunately, ATS II did not attain the desired circular orbit because the second stage engine failed to restart. Nevertheless, data were obtained from many of the experiments.

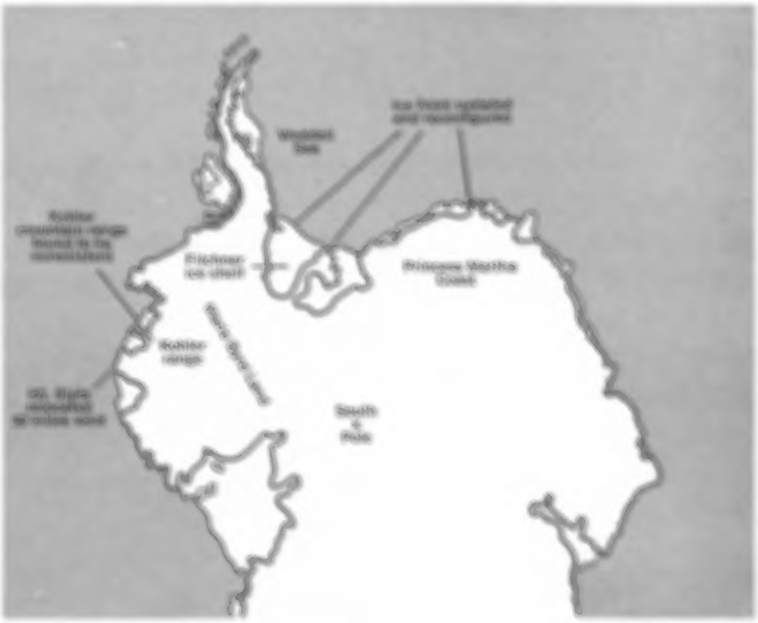
ATS III was launched November 5, 1967. Another spin-scan camera, able to take full color pictures, was carried along this time, plus an Image Dissector Camera System. The ATS role is to test such equipment for possible use on operational weather satellites. A third experiment concerns satellite navigation systems—more specifically the Omega Position Location Experiment (OPLE). The OPLE navigation concept is not directed toward aiding navigators aboard aircraft and ships but rather in the direction of locating unmanned instrument platforms sent out for the purpose of gathering meteorological and oceanographic data. OPLE can interrogate such instrument platforms for data and relay the data to a central facility. Eventually, however, OPLE could also be applied to air traffic control, since an airplane can also be thought of as a moving instrument platform.

The Earth: The Big Picture

From their vantage points 100 miles and more up, satellites can see large-scale patterns and phenomena that Earthbound observers cannot—either because they are too close to them or are actually immersed in the phenomena. Cloud patterns, already mentioned, are obvious examples, but we can add agricultural patterns, ocean currents, geological formulations, buried archeological sites, and many more.

One of our problems in studying the Earth is that we are too close to it; this is certainly the case in mapping large weather systems where high altitude meteorological satellites are unbeatable. Aircraft help some in seeing the Earth in the large, but satellites fly considerably higher and see the big picture much better. The questions are: What can satellites see of importance from so high up, and how can this information be put to practical use?

Besides scrutinizing the Earth below in visible light, satellite infrared and microwave sensors can scan the oceans and continents at longer wavelengths. The infrared and microwave radiation emitted by the Earth depends upon surface temperatures and the composition of surface materials. The use of infrared sensors on weather satellites to monitor atmospheric processes, such as the Earth's heat budget, has already been described, but the same sensors can also be used to study the Gulf Stream, detect forest fires, and locate subterranean heat sources.



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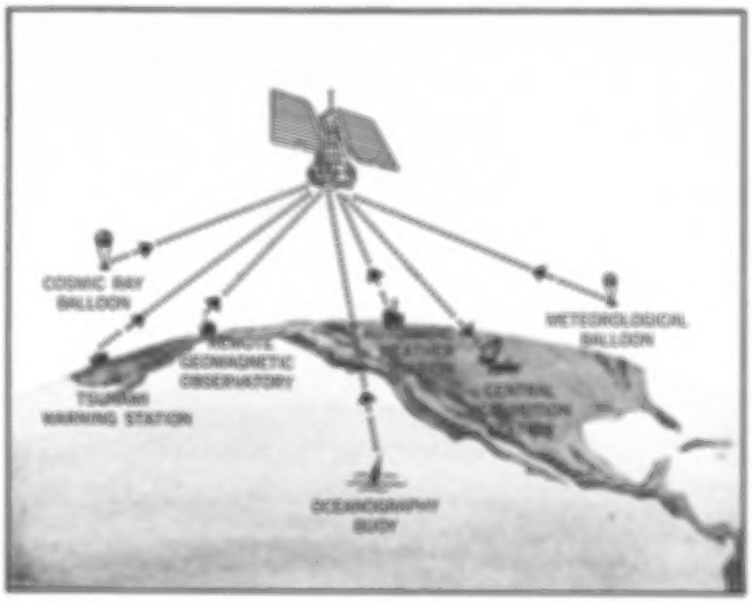
21 *The U.S. Geological Survey has used Nimbus pictures to update and correct its maps of Antarctica. More advanced survey satellites will be capable of much greater resolution.*

22 *Schematic showing how satellites can be used to relay data taken by unmanned instrument platforms to centralized data collection points.*



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The key elements in seeing more than weather from satellites are: (1) Look harder; that is, use more magnification; (2) Study the infrared and microwave emissions from the Earth; and (3) Subtract out the effects of the Earth's atmosphere. Once these things are done, some surprising possibilities emerge, although it should be stressed that considerable research and development work lies ahead before these applications can be realized.

Map preparation. Transportation networks and urban/rural settlement patterns, at some future time, may be quickly and economically mapped to facilitate highway and pipeline routing.

Agricultural census and crop prediction. Different crops may be identified by satellite sensors, leading to frequent and economical forecasts of the world's food supply. Furthermore, invasions of insects and disease may be spotted early and countermeasures organized on the basis of satellite data.

Detection of forest fires. Satellite infrared sensors may scan the forests in the U.S.

Water resource surveys. Satellites may help keep accurate inventories of fresh water supplies for the entire country. Droughts may be predicted and, eventually, water flow may be controlled to offset droughts. Satellite surveys may also help plan new dams and artificial watercourses.

Mineral resource surveys. Satellites may survey quickly and cheaply the huge areas of the world that are inadequately explored geologically. Satellites may identify particularly promising areas that it might take ground survey crews many years to find.

Discovery of archeological sites. For the same reason, buried cities, ancient roads, mound sites, and other partially obscured relics of past civilizations may be discovered.

Air pollution surveys. Like forest fires, sources of air pollution may be spotted from a satellite, mainly through the way they absorb light. The spread of pollutants under various wind and terrain conditions could also be studied with an eye to better control.

Location of hydrothermal energy sources. Infrared sensors may spot geothermal anomalies on the Earth, such as those at Yellowstone, where natural heat may be converted into electrical power.

Oceanography. Despite the more than 100 miles between an earth satellite and the sea, the satellite may turn out to be one of the most powerful oceanographic tools devised. Satellite cameras can monitor such factors as pollution patterns, beach erosion, river run off, and sedimentation patterns. Temperature patterns in the sea have already been distinguished by weather satellites, and knowledge of temperatures can improve the fish harvest. Wave heights can be mapped over large areas of the ocean by measuring the "Sun glint" off the sea surface. In a different vein, satellites can receive radio transmissions from large numbers of unmanned oceanographic buoys and relay their data to central land facilities.

The practical value of the satellite as a monitor and explorer of the Earth's surface is just beginning to be appreciated.

On the basis of preliminary conclusions drawn from studies and the results obtained from remote sensor experiments on aircraft, an Earth Resources Technology Satellite (ERTS) Program plan has been drafted by NASA in cooperation with several other interested departments and agencies of the Government. Testing of an early version of such an experimental satellite should be possible in the 1970's.

Additional Reading

For titles of books and teaching aids related to the subjects discussed in this booklet, see NASA's educational publication EP-48, Aerospace Bibliography, Fourth Edition.

NASA-Langley, [illegible]

America In Space | The First Decade

NASA Spacecraft

National Aeronautics and Space Administration

America
In
Space:
The
First
Decade

This is one of a series of booklets published on the occasion of the 10th Anniversary of the National Aeronautics and Space Administration.
These publications are not intended to be comprehensive history, nor do they deal with all the facets of NASA's aeronautical and space activities. Rather they are overviews of some important activities, programs and events written for the layman in terms of the several science disciplines.

Each of these subjects is treated in more depth in other NASA publications and in scientific journals.

1 October 1968

Titles in this series include:

I Space Physics and Astronomy
II Exploring the Moon and Planets
III Putting Satellites to Work
IV NASA Spacecraft
V Spacecraft Tracking
VI Linking Man and Spacecraft
VII Man in Space

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Propulsion
Spacecraft Power
Space Life Sciences
Aeronautics
Space Age By-products
Materials

NASA SPACECRAFT

by William R. Corliss

National Aeronautics and Space Administration, Washington, D.C. 20546,

Introduction

It is ten years since the National Aeronautics and Space Administration was created to explore space and to continue the American efforts that had already begun with the launch of Explorer I on January 31, 1958. Many changes have occurred since that tumbling, 31-pound cylinder went into an Earth orbit. "NASA Spacecraft" represents one of the broad avenues selected by NASA as an approach to its objective of making widely known the progress that has taken place in its program of space exploration. This report is a vivid illustration of the changes that have occurred and the complexities that have developed. Here one finds descriptions of the present family of spacecraft—some small, some large; some spin-oriented, some accurately attitude-controlled; some manned, some automated; some in low orbits, some in trajectories to the Moon and the planets; some free in space until they expire, others commanded to return to the Earth or to land on the Moon.

Oran W. Nicks
Deputy Associate Administrator for
Space Science and Applications

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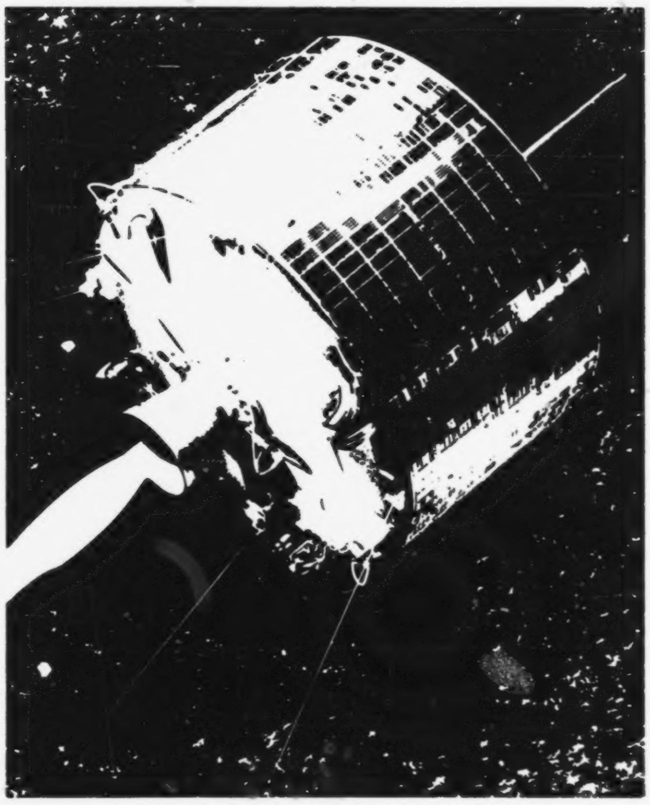
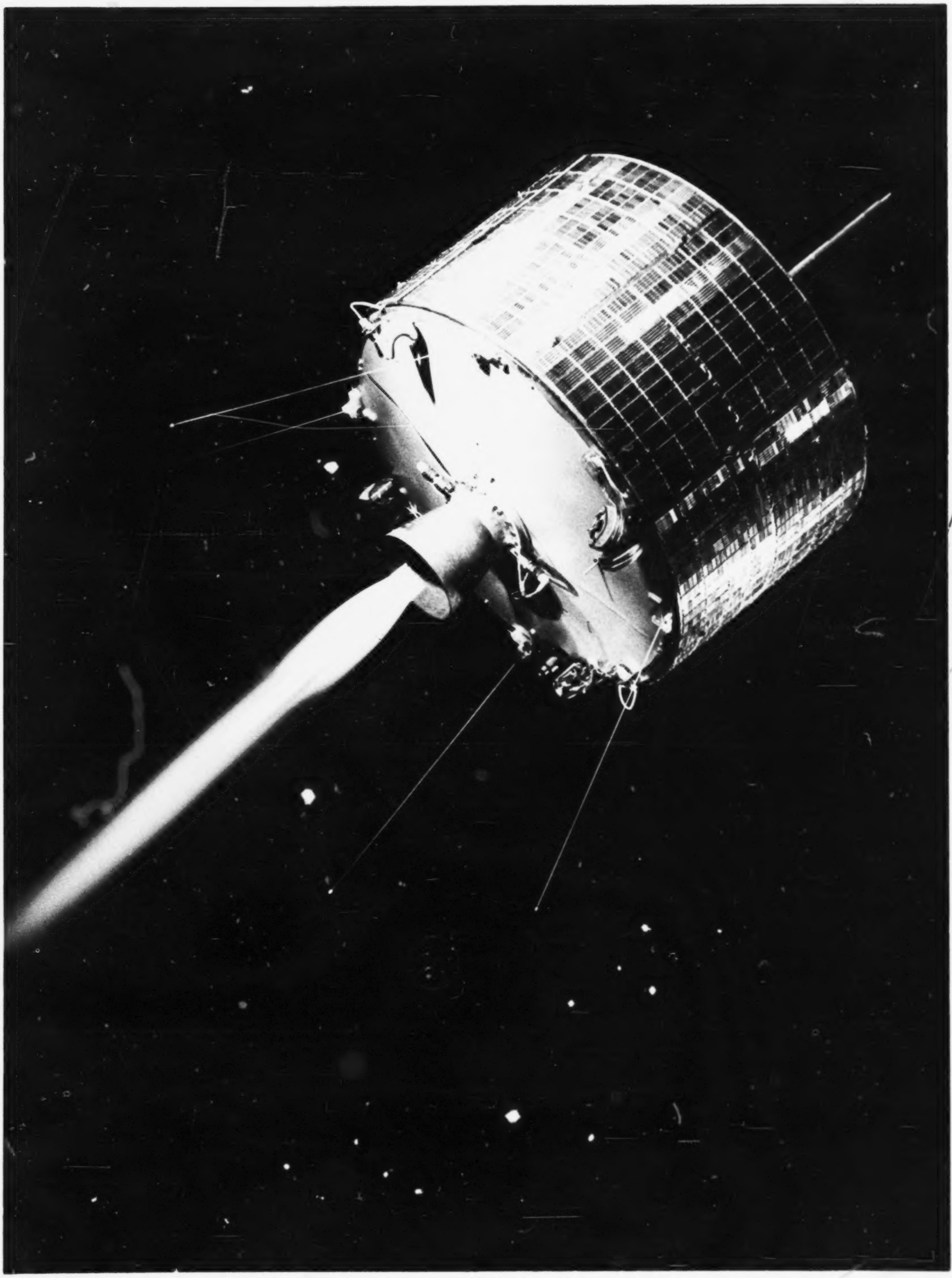




NASA Spacecraft

Spaceships And Spacecraft

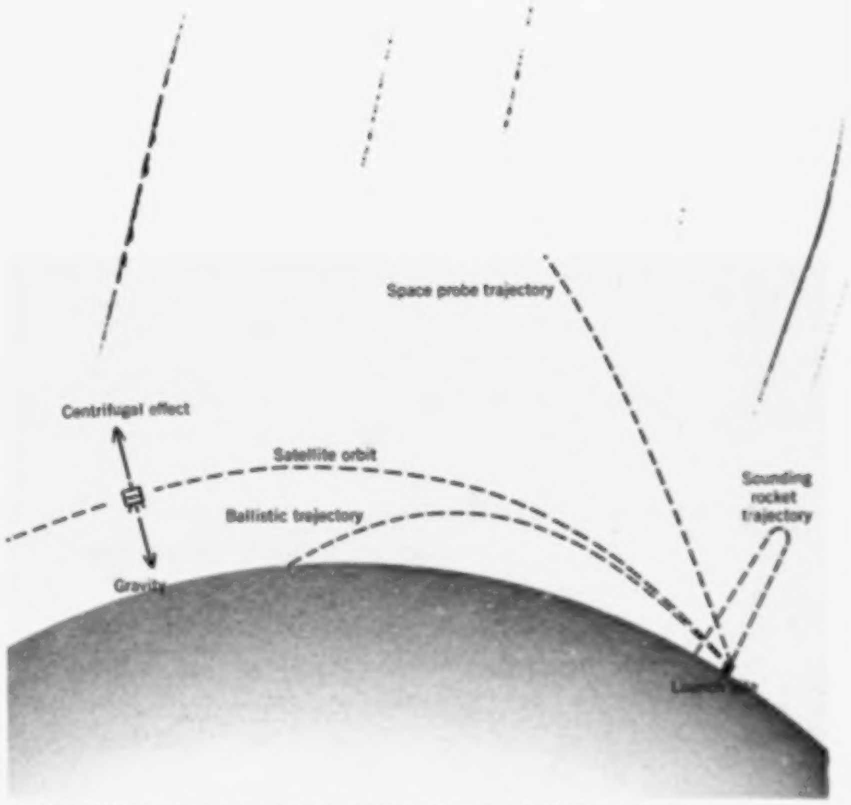
To Jules Verne, a spacecraft was a huge aluminum bullet fired toward the Moon from a gigantic cannon buried in Florida soil, not too far from Cape Kennedy. In 1865, when Verne's "De la Terre a la Lune" appeared, spacecraft were conceived as well-appointed extensions of the drawing room, and the gentlemen who traveled in them likely as not wore top hats and formal attire. This romantic view of the spacecraft persisted well into the Twentieth Century. To distinguish these visions of fiction from today's complex space machines, we call the former spaceships and the latter spacecraft.

A spacecraft is any vehicle that operates above the sensible atmosphere; that is, above the altitudes attainable by research balloons and aircraft—approximately 100,000 feet of altitude.

In the first ten years of space flight, over 600 satellites have circled the globe. Even so, the satellite has been greatly outnumbered by the sounding rocket, a spacecraft that breaks through the atmosphere into space for only a few minutes. Although sounding rockets do not linger long at high altitudes, they have made major discoveries in space science, such as the existence of X-ray stars.

A satellite is a spacecraft that has been given sufficient velocity by its launch rocket to be placed in orbit. Ultimately the trace of atmosphere still present at satellite altitudes will slow the satellite down and gravity will pull it back to Earth. The distinction between a satellite and a long range rocket is that the satellite makes one or more complete circuits of the Earth.

In 1955, when the United States decided to launch a small research satellite during the International Geophysical Year, the engineers assigned to the task did not think of Jules Verne's elegant, well-padded projectile; they thought about extending sounding rocket technology. For a while, the first



1 *Satellites stay in orbit because the centrifugal effect due to their horizontal velocity just cancels the gravitational force trying to pull them back to Earth. Sounding rocket and ballistic trajectories are segments of ellipses. Space probes leave the Earth's gravitational field completely.*

U.S. satellite project was called the LPR, the Long Playing Rocket. Jules Verne may have the last laugh, however, because the United States and Canada have seriously considered launching small satellites with the help of a rebored 16-inch naval cannon.

Spacecraft that are shot deep into space and escape the gravitational pull of the Earth completely are called space probes. Depending on the target; they are called lunar, planetary, and deep space probes. Deep space probes are placed in orbit around the Sun to study the solar wind and interplanetary magnetic field. In essence they are artificial planets. One of three things may happen to a probe launched toward the Moon or one of the planets: (1) a near miss or fly-by, (2) injection into orbit around the body, or (3) impact on the surface, with either a hard or soft landing. Fly-by probes usually go into orbit around the Sun after planetary encounter. Lunar probes may swing around the Moon and settle down to become Earth satellites.

Spacecraft may also be classified as manned or unmanned; as recoverable or unrecoverable. All manned spacecraft are made recoverable; so are most sounding rockets. Those unmanned satellites that carry film packs or biological specimens are made recoverable by adding retrorockets that force the spacecraft to reenter upon command from the ground.

Spacecraft may be either active or passive. A passive satellite transmits no radio signals to Earth but may reflect them back. NASA's Echo balloon satellites are good examples of passive satellites. They are big enough to see visually, and by their motion reveal the air density where they orbit. Active satellites emit radio signals to make tracking easier and to transmit data from their instruments to ground stations. When a satellite radio signal fades naturally or is intentionally cut off by a killer timer, the satellite becomes inactive or dark.

Satellites are also classified by their orbits. A polar satellite orbits over the Earth's polar regions. A synchronous satellite orbits the Earth in the same length of time it takes the Earth to make one revolution on its axis. If the synchronous satellite is also an equatorial satellite, it will seem to remain in the same position in the sky at all times. It is then a stationary or geostationary satellite.

The final taxonomic breakdown depends upon the functions or uses of satellites. NASA divides its satellites into three categories:

1. *Scientific satellites,* which carry instruments to measure magnetic fields, space radiation, the Sun, and so on. Examples: NASA's Explorer series, the OGO series.
2. *Applications satellites,* which have utilitarian purposes. They help forecast the weather, extend Earth communications, survey the Earth, find mineral deposits, test equipment, etc. Examples: the TIROS weather satellites, the Syncom communication satellites.
3. *Manned satellites,* which are designed to check out equipment and man himself in preparation for the manned lunar landing and other manned space missions.

Spacecraft obviously differ greatly in size, shape, complexity, and purpose. Nevertheless, most require power supplies, radio transmitters, a means for orientation in space, as well as other equipment. Spacecraft can be described in general terms first, by showing how they work; second, by describing the hundreds of NASA satellites, probes, and sounding rockets launched since the Agency's founding in 1958. Fortunately, they can be collected into handy families. For example, a TIROS family of weather satellites exists; so does a Gemini class of manned spacecraft.

How Spacecraft Work

Of Systems and Subsystems

Automobiles and spacecraft are both man-machine systems. In the auto, a motor turns the wheels, a steering wheel changes its direction, a heater keeps the occupant warm in the winter. Spacecraft have subsystems that help man attain his objectives.

Modern spacecraft are driven—like the car—either by an astronaut or by a human controller on the ground connected to the spacecraft by a radio link.

Of all the subsystems that make a spacecraft work properly, nine are critical:

Subsystem	Function
Power supply	Provides energy to all other subsystems. Needed by all active satellites.
On-board propulsion	Generates thrust for rendezvous, orbital changes, soft landings, deorbiting, etc.
Communication	Relays information to Earth and receives commands in return.
Attitude control	Points the spacecraft on command. Stabilizes its orientation (attitude).
Environment control	Maintains suitable temperatures and atmospheres for man and equipment.
Guidance and control	Interprets commands from Earth and internal memory bank and sees that they are carried out by the appropriate subsystems.
Computer	Carries out computations.
Structure	Supports and maintains spacecraft configuration.
Engineering instrument	Measures status of spacecraft in terms of temperature, operating modes, etc. Also monitors astronauts.

A simple, passive balloon satellite may have less than 100 parts and require only the structure subsystem. A soft lunar lander may contain 20,000 parts and use all nine subsystems.

Spacecraft are really extensions of man that enable him to explore the cosmos and make use of the Earth's resources. Spacecraft can extend man's hands to the Moon and planets, as they have already done with the Surveyor surface samplers. Man and a radio-linked spacecraft make a remarkable and useful man-machine partnership.

The Power Supply Subsystem

Only a few watts bring a spacecraft to life and make it a useful extension of man. Satellites consuming less than 10 watts of power discovered the Van Allen belts and the solar wind. The biggest satellites and space probes require only a few hundred watts for their operation. A kilowatt or two will keep man alive and in touch with the Earth. While spacecraft may not be power guzzlers of the same order as the American home, there are no gas pumps or electric power lines out in space to keep them running. Fuel must be carried along or energy must be extracted from sunlight.

Sounding rockets have found batteries adequate for their brief forays above the atmosphere. The early satellites also carried batteries into space, but they lasted only a few weeks. To improve satellite longevity, the Vanguard I satellite carried the first solar cells aloft in 1958. Since then, almost all satellites and space probes have their complements of the little silicon wafers. The short-mission manned satellites are the major exceptions.

Solar cells were invented at the Bell Telephone Laboratories in 1954. They are only an inch long, a half inch wide, and a few hundredths of an inch thick—about the size of a razor blade. When sunlight

2. Closeup view of the Applications Technology Satellite (ATS) showing the thousands of solar cells bonded to the satellite's cylindrical surface.

strikes a solar cell, roughly 10% of its energy is converted into electrical energy; the remainder (90%) is reflected or turned into heat. The electrical current flows between the layers of electron-rich (n-type) and electron-poor (p-type) silicon layers that make up the thin solar-cell sandwich. Although a single solar cell generates only a fraction of a watt, hundreds and thousands are commonly hooked together to provide the spacecraft with the power it needs. To gather enough sunlight, solar cells are fastened on the body of the spacecraft, or on extendable paddles.

Solar cells do not eliminate batteries. Because many Earth satellites spend much of their life in the Earth's shadow, solar cells must charge up batteries during the satellite day so that power will be available during satellite night. In low orbits, the satellite day-night cycle lasts only an hour and a half. Consquently, the solar cell-battery combination charges and discharges several thousand times a year.

Why weren't solar cells used on the Mercury and Gemini manned missions? They would have taken too much room—roughly a hundred square feet per kilowatt. Batteries alone are too heavy for missions lasting more than a few days. The Mercury spacecraft did employ batteries, but with the Gemini series NASA switched to fuel cells.

A fuel cell is really a continuously fueled battery. A fuel, such as gaseous hydrogen is made to react with oxygen on a high-surface-area electrode. Electricity and a combustion product—water in this case—result. There is no flame during fuel cell combustion, just as there is none in a flashlight dry cell, although a little heat is generated because energy conversion is not 100% efficient. As fuel and oxidizer are consumed in the fuel cell, they are replenished from external tanks. When manned missions are longer than a few days, the fuel cell plus fuel and oxidizer tanks are lighter than batteries.

Summarizing, batteries are used on most sounding rockets; solar cell-battery combinations on most other unmanned spacecraft; and fuel cells on most manned spacecraft.

The Onboard Propulsion Subsystem
The only practical way to bring an astronaut down out of orbit is to slow the spacecraft with a small rocket and cause it to reenter the Earth's atmosphere. The Surveyor lunar probe also required a rocket engine to slow it from several thousand miles per hour to a feather-like touchdown that did not hurt its instruments. Geostationary satellites, such as the Syncoms, must apply bursts of thrust to maintain their orbits (station keeping).

Onboard rockets are many times smaller than their huge counterparts that we see on the launch pad, but they are equally sophisticated. For one thing, the propellants must be storable; that is, they must survive in the space environment for days or weeks before they are burned. For this reason, the usual launch rocket fuels (kerosene or liquid hydrogen) and oxidizer (liquid oxygen) are replaced by a solid fuel, a monopropellant (like hydrogen peroxide), or a storable bipropellant.

If liquids are selected for the onboard rocket, there may be no gravitational force to pull them into the engine when they are needed; say, in orbit or halfway to Mars. Consequently, NASA has developed squeezable bladders, pistons, and other positive expulsion containers that force fluids into the engine without assistance from gravity.

Onboard rockets present one more difficult requirement: they must fire and shut off upon command from Earth or the spacecraft's internal memory. Maneuvers in space can be very touchy and delicate, particularly when the target is a planet 100,000,000 miles away or a specific crater on the Moon.

The Communication Subsystem
Radios link spacecraft with the Earth-based data acquisition system that ultimately connects the spacecraft to man. Radios seem rather prosaic these days, but spacecraft communication is not quite as easy as turning on channel 4 on the TV. First, there is the problem of distance—hundreds of miles in the case of deep-space probes. Second, some Earth satellites are prodigious data gatherers and must transmit huge quantities of information. Both distance and data volume can be achieved if the spacecraft has a big voice or the Earth receiving station has big ears. A big spacecraft voice infers a high transmitter power; but power is a scarce commodity in space and the big-ear approach is favored. Thus NASA's data acquisition stations point large [illegible]5-foot and 210-foot paraboloidal antennas at passing satellites and space probes out in the depths of space.

Very high frequencies have to be used for spacecraft communication. They have to be high enough to penetrate the Earth's ionosphere (over 20 MHz*) and low enough so that the signals are not absorbed by atoms and molecules in the atmosphere (under 300 MHz). Terrestrial radio noise created by man and thunderstorms interfere at the lower frequencies. As a result, most space communication systems operate between 100 and 3000 MHz.

Spacecraft do not send radio messages back to Earth continuously, although tracking beacons often transmit all the time. Most spacecraft transmitters are activated upon the receipt of a radio command from Earth. Much of the time spacecraft are not within range of Earth-based receiving stations, and it would be wasteful of power and valuable data to send signals all the time. Instead, when a spacecraft comes over the horizon toward a data acquisition station, it is commanded to read out its memory—usually a tape recorder. The spacecraft then dumps these data in a burst to the radio ears waiting below.

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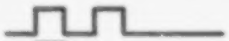
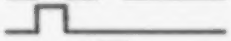
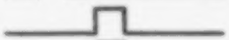
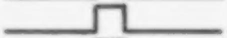
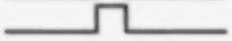
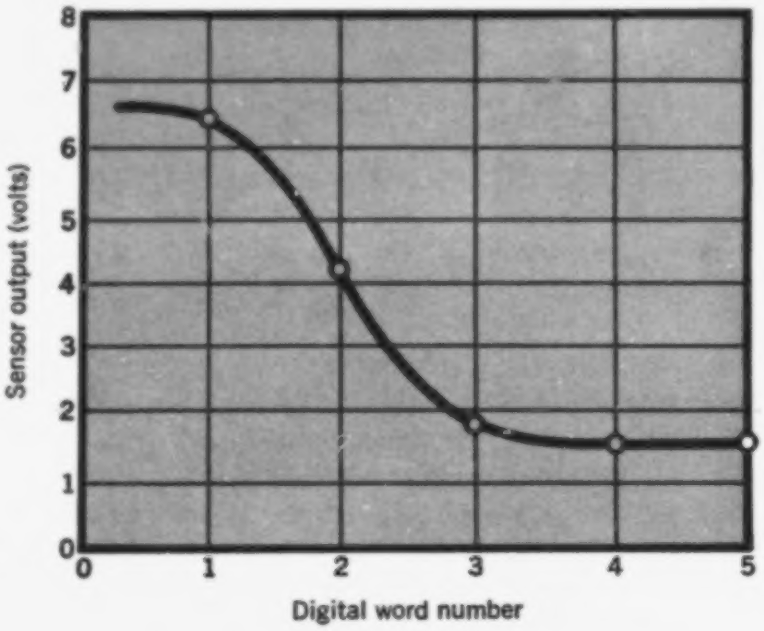
*1 MHz = one megahertz = 1,000,000 cycles per second.

3 *A continuously varying instrument reading can be approximated by a series of digital binary data words. The more bits used per word, the more accurate the analog-digital conversion. In this illustration, for example, a three bit word limitation means that sensor readings 1.8, 1.6 and 1.7 all translate into binary language as 010.*

Data word no.	Decimal sensor reading	Three-bit data word	Pulse trains
1	6.3	110	
2	4.1	100	
3	1.8	010	
4	1.6	010	
5	1.7	010	



Collectively, NASA ground stations often acquire more than 50 miles of data on magnetic tape in a day. When an OGO satellite dumps its memory, it transmits the equivalent of a couple of novels in a few minutes. In 1958 the problem was getting any data at all from space; today, NASA must cope effectively with vast quantities of it. Computer data processing on the ground is part of the answer. The tendency is for spacecraft to talk directly to ground-based computers in computer language; that is, the binary number system, which is based upon the number 2 instead of 10.* The computer reduces the data and even draws graphs for the experimenters.

The Attitude Control Subsystem
On Earth we find it easy to keep our vertical orientation by pushing against the ground with our feet. In space, though, there is little to push against, and there are a surprising number of forces that tend to disturb the orientation (attitude) of a spacecraft.

The two main tasks of a spacecraft's attitude control subsystem are stabilization and pointing. Stabilization means keeping the spacecraft oriented in a specific direction despite natural forces to the contrary. Spacecraft stabilization can be compared to keeping a light car on the road in the presence of strong wind gusts. Some spacecraft need to be pointed at selected targets as well as being stabilized. The Orbiting Solar Observatories, for example, must lock onto the Sun and follow it with their instruments. Weather satellites have to keep their cameras trained on the Earth. Both stabilization and pointing require that the attitude control subsystem generate turning forces or torques on the spacecraft.

NASA has studied the natural forces existing in space with an eye to overcoming them and even harnessing them for attitude control. Sunlight, for example, exerts a small but significant pressure on all spacecraft surfaces it hits. Unless a counter-torque is created by the attitude control subsystem, this pressure can twist the spacecraft into undesired orientations. Occasionally, solar pressure can be put to positive use; some of NASA's Mariner planetary probes carried special vanes that applied solar pressure to attitude control the same way that sails make use of the wind in propelling sailboats.

Gravity, too, is pervasive and persuasive; it always tries to pull the long axis of a satellite around so that it points at the Earth. Our Moon is gravitationally stabilized in this way by the Earth, always keeping one face toward us. Many NASA satellites take advantage of this naturally stabilizing force by paying out long booms or pendulums. The Earth's field then swings these and the satellite instruments around so they face the Earth. This is termed gravity-gradient stabilization.

The Earth's magnetic field is also useful. By building coils of wire in satellites and connecting them to the spacecraft power supply, the satellites

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**In the binary language: 001=1, 010=2, 011=3, 100=4, 101=5, and so on.*

can be made into electromagnets. When electrical current is applied, the satellite's magnetic field interacts with that of the Earth, and the satellite will turn like the armature of a motor. Many NASA satellites are magnetically stabilized.

The majority of satellites are spin-stabilized. When they are propelled into orbit, the final stage of the launch rocket gives them a twist that spins them at, say, 30 rpm. This spin, or its angular momentum, stabilizes the spacecraft against the influences of solar pressure, meteoroid impacts, and other disturbing torques in the same way the spin of a rifle bullet keeps it from tumbling.

Spacecraft like the Surveyors and Orbiting Geophysical Observatories need something more powerful than gravitational and magnetic attitude control schemes. Strong, controllable torques can be created by pairs of small rocket engines mounted on the periphery of the spacecraft. The rockets may be small versions of the onboard engines just described, or they may be bottles of compressed gas with electrically controlled valves. For very tiny, precisely measured bursts of thrust, NASA engineers have developed thrusters that shoot little bursts of gas. All attitude control schemes depending on the rocket principle expel mass. Since mass is limited on spacecraft, so is the amount of pointing and stabilization achievable by mass expulsion.

Whenever a motor in a spacecraft starts up, the entire spacecraft experiences a twist in a direction opposite from that on the motor shaft. The Law of Conservation of Angular Momentum demands this. Again, a potential destabilizer can be turned to positive uses. Gyroscopes and inertia wheels are just motors with heavy rotors. When their speeds of rotation are changed, they exert torques on the spacecraft. A set of three gyros mounted with shafts parallel to each of the spacecraft's three degrees of freedom can control all aspects of spacecraft orientation. Gyros and inertia wheels, of course, do not expel valuable mass when they change spacecraft attitude, but they are limited in the sense that they can spin only so fast without damaging themselves. Suppose a meteoroid hits a solar-cell panel and starts the spacecraft spinning. The gyro controlling that spin axis will increase its speed of rotation, trying to build up enough torque to stop the spacecraft spin. However, if the disturbance was too great, the gyro may reach its maximum speed without stabilizing the spacecraft. In this case, the gyro is said to be "saturated." By firing an onboard attitude control rocket or gas jet, the gyro can be desaturated.

The Environment Control Subsystem

Controlling the environment means insuring that man and his instruments can survive in space. For man, this means taking an atmosphere along and enclosing him in a capsule that keeps out the harsh environment of outer space, in particular the vacuum, the Sun's ultraviolet rays, and the searing heat of atmospheric reentry.

Other environmental threats are: micrometeoroid damage, radiation damage from the Van Allen belts, and the high-g forces of rocket launch and spacecraft landing.

A unique problem faces the engineers who design NASA's planetary probes. These craft, if they are to enter other planets' atmospheres, must be able to withstand the high temperatures of biological sterilization. The purpose of spacecraft sterilization is the avoidance of contaminating the other planets of the solar system. Were organisms of Earth origin inadvertently introduced into the ecology of another planet, the opportunity to study an extraterrestrial life system in the natural state would be forever lost. If life has arisen elsewhere, the reverse problem exists—that of excluding extraterrestrial organisms from manned spacecraft and from Earth itself upon the return of astronauts.

Thermal control is a serious problem for the vast majority of spacecraft. If instruments get too hot or cold they are apt to malfunction. Offhand, the problem would seem to be one of heating spacecraft in the cold of outer space. It is true that an object placed far out in interstellar space will soon radiate away most of its sensible heat and attain a temperature a few degrees above absolute zero. But in Earth orbit, the Sun and the sunlit side of the Earth both radiate considerable heat to a satellite. In fact, the average temperature of an Earth satellite will not be too different from room temperature. The problem lies in that word average.

When a satellite enters the Earth's shadow, it immediately begins radiating its sensible heat to cold, starry space, and to the night side of Earth, which fills almost half the sky. Some heat is received back from Earth, since even the night side averages well above freezing. Earthshine is usually not enough, particularly if the satellite is in a high orbit that keeps it in the Earth's shadow for several hours. Some heat comes from satellite electrical equipment; special heaters can be added at cold-sensitive spots. Ultimately, the heat energy comes from the power supply.

The Surveyor lunar landers faced severe thermal problems during the two-week, cold lunar nights. NASA made no attempt to maintain normal operating temperatures in the Surveyors during these periods; missions were suspended until the next lunar day. In some cases, the heat of the Sun was able to revive the frozen spacecraft.

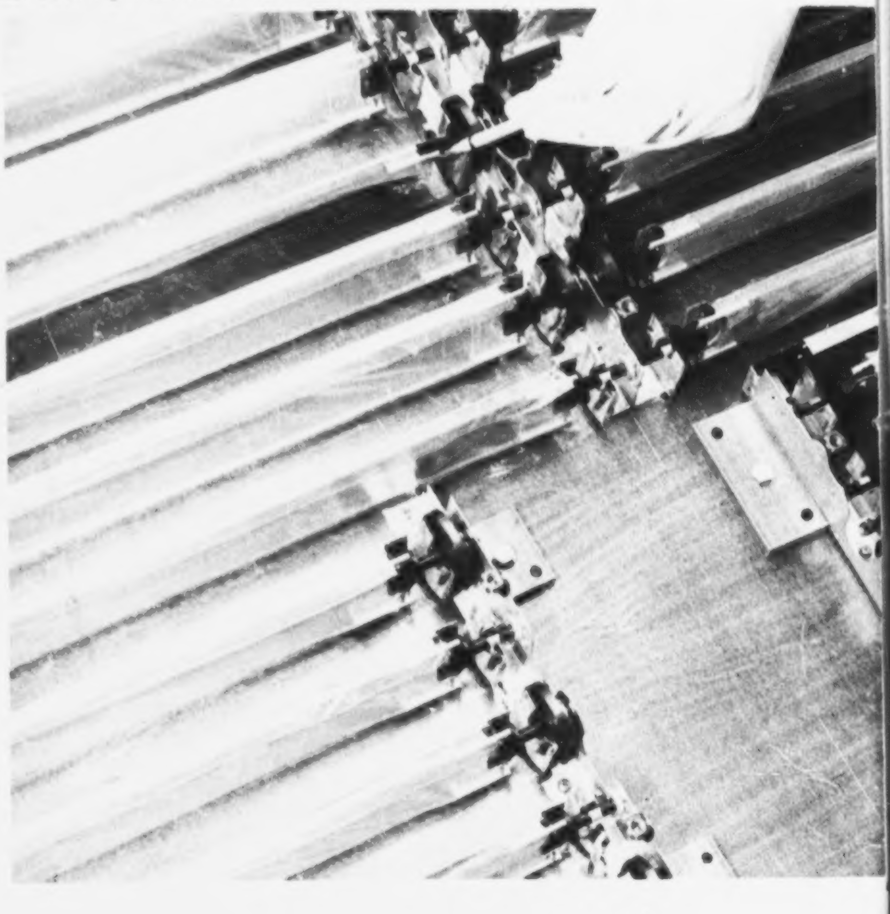
Spacecraft that are in the Sun all of the time must deal with overheating. All space probes, some high-orbit satellites, and those satellites that keep one face oriented toward the Sun (the OSOs, for example) must get rid of excess heat by radiating it to empty space. Special metallic conduits (heat pipes) are sometimes installed to conduct internal heat out to the spacecraft surface or from the hot side to the cold side. The amount of heat escaping from the side of the spacecraft facing cold space can be automatically adjusted by thermostatically controlled louvers; which are Venetian-blind-like vanes that expose the hot internals of the spacecraft.

Astronauts must be kept cool, too, but a breathable atmosphere is even more critical. On short manned missions, such as the Gemini satellite flights and the Apollo Moon voyage, bottled atmosphere can be carried along from Earth. For missions exceeding a month or so, this approach would cost too much in terms of weight. The alternative is a spacecraft atmosphere that is continuously regenerated or renewed.

The Guidance and Control Subsystem

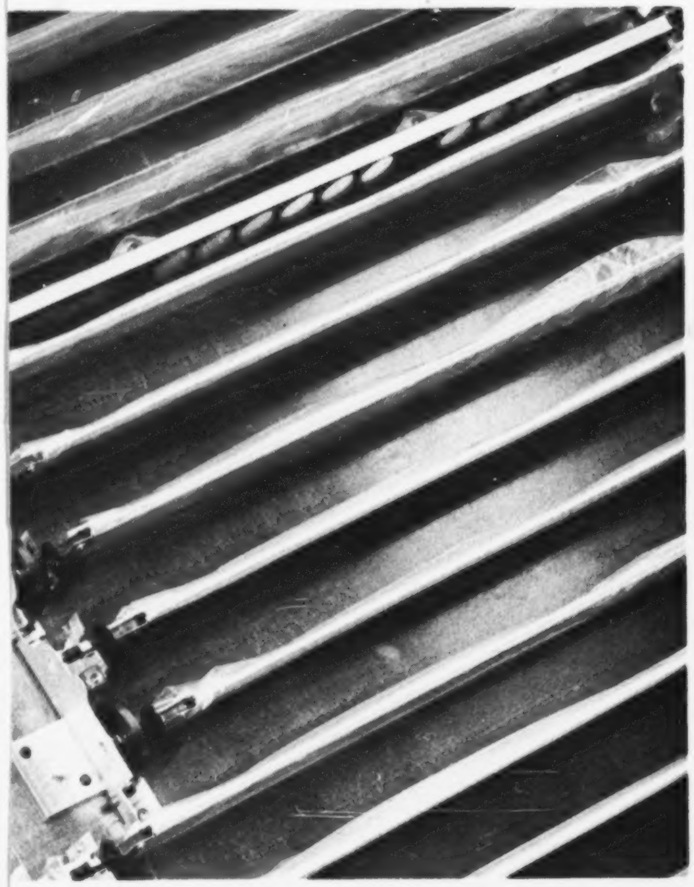
Steering spacecraft safely to their targets is the task of the guidance and control subsystem. Consider a spacecraft trying for a soft landing on the Moon. The attitude control subsystem has already turned the spacecraft around so that its retrorocket and

4 The thermal control louvers of OGO. These open like a Venetian blind to allow the hot spacecraft interior to cool by radiation to dark space.



landing radar are pointed at the Moon. Radar signals tell the spacecraft guidance and control subsystem the speed of descent and the distance from the surface. Built into the spacecraft memory is information telling the spacecraft when to fire its retrorocket on the basis of radar data. The guidance and control subsystem continually compares the real radar signals with the signals its memory says it should be receiving. When the proper spacecraft velocity and distance from the Moon are reached, a command to fire retrorockets is dispatched to the onboard propulsion subsystem. The rocket fires until radar data indicate that touchdown will occur at near-zero velocity. This is the essence of control: comparison of real performance with desired performance and the commanding of the spacecraft to eliminate any discrepancy between the two.

Most spacecraft control functions are much simpler than soft landing on the Moon. A good example is the cutoff of a satellite transmitter to free a frequency channel for new spacecraft. This simple act is accomplished by a killer timer that disconnects the power supply after six months or a year of operation.



The lunar lander and killer timer examples illustrate what engineers call closed and open-loop control. The lunar landing requires continuous feedback of information telling the guidance and control subsystem how well it is doing its job. In such closed-loop-control situations the opportunity for corrective action exists. With the killer timer, action is irrevocable.

A modern spacecraft possesses dozens of sensors that tell the guidance and control subsystem (which often includes the human controller on the ground via the communication link) the *status* of the spacecraft. Thermometers take spacecraft temperature; gyros, star trackers, and Sun sensors measure spacecraft attitude; and voltmeters and ammeters relate how the power supply is performing. Less obvious are the signals that tell the human controller the positions of critical switches that fix the spacecraft's mode of operation. For example, it is important to know which experiments are on and which are off. Collectively, such status signals are termed housekeeping data.

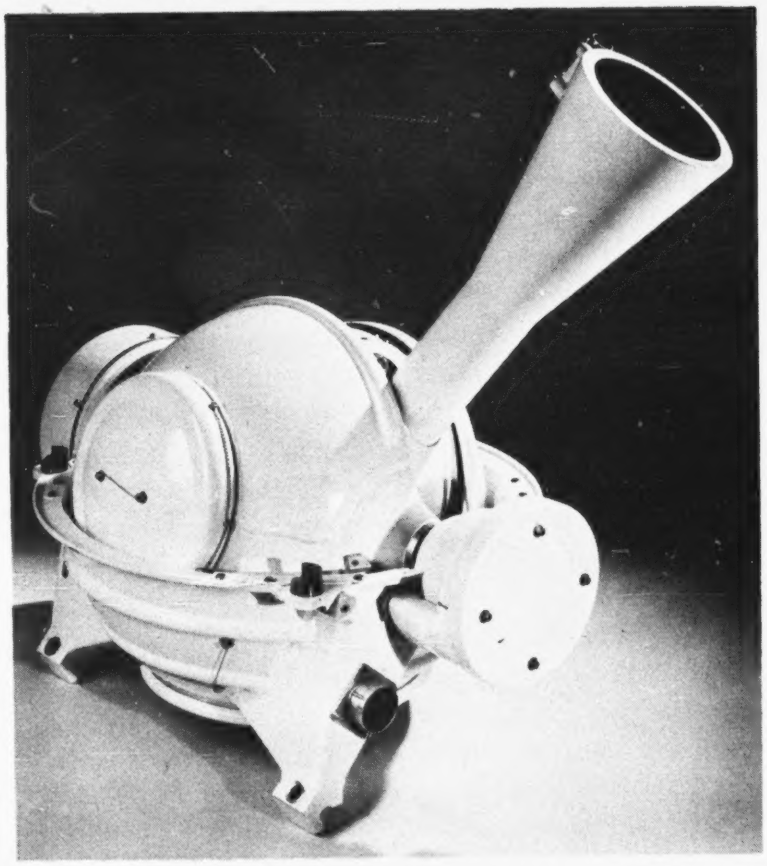
The Computer Subsystem

Computers are generally thought of as large machines that belong on the ground rather than on spacecraft. Several spacecraft functions, however, have combined to make computers integral parts of large, modern spacecraft.

One of the simplest jobs for a spacecraft computer is analog-digital or AD conversion. Many spacecraft instruments generate continuously varying or analog signals. But spacecraft usually communicate with the ground in digital language. To translate instrument readings into the lingua franca of space, small AD converters are attached to analog-speaking equipment. In reality, AD converters are little, special-purpose computers.

Sometimes computations are required on highly automatic spacecraft, such as the Orbiting Astronomical Observatory (OAO). The OAO star tracker readings, for example, must be transformed into the proper geometric coordinates if the OAO

5 The Orbiting Astronomical Observatory (OAO) star tracker is programmed to search for and follow certain guide stars. Once the telescope has locked onto a guide star, the star tracker sends its coordinates to the guidance and control subsystem. With several such fixes, the OAO can compute its attitude in space and then change the orientation of its instruments to pick up any given stellar target.



attitude control subsystem is to know where to point the spacecraft telescope. Such transformations involve a great deal of trigonometry; something a little onboard computer does very nicely. Small computers have also been installed on some of the manned spacecraft to help the astronauts with guidance and navigation computations.

In principle, all computations could be carried out by sending the problem to ground-based computers through the medium of the communication subsystem. Answers would be returned the same way. NASA did use this approach with some of the earlier satellites, but as spacecraft became more complex it turned out to be too much of a burden on the communication link. Now ground-based and onboard computers share the load.

The Structure Subsystem

The structure subsystem forms the backbone of the spacecraft. It supports, unites, and protects the other subsystems. Basically, a spacecraft's structure can be divided into two parts: the central core or skeleton and the deployable appendages (antennas, booms, solar cell paddles) that unfold once the spacecraft is out in space.

Almost all spacecraft are symmetrical about at least one axis. There are two good reasons for this: (1) many spacecraft are spin-stabilized and need symmetry around the spin axis to prevent wobbling; and (2) launch accelerations are powerful and are best resisted by an axial thrust structure. These are the reasons why so many spacecraft are cylinders, regular prisms, or spheres.

Many exceptions exist. In fact, spacecraft are a geometer's delight. One finds cubes, parallelopipeds, polyhedrons, and cones. The balloon satellites are a class by themselves. So are the manned space capsules with their blunt reentry shields.

Lightness is a premium commodity on spacecraft. For this reason NASA has developed a whole spectrum of aluminum, magnesium, and plastic structures that weigh little but resist the stresses of space use. The steels are restricted in use because of their high densities and also because they are magnetic—an undesirable property when one is trying to measure the extremely low magnetic fields in space. One of the major structures on manned spacecraft is the protective thermal shield needed during reentry through the atmosphere. NASA generally makes its reentry shields from a plastic containing embedded glass fibers. As the air in front of the reentering spacecraft is heated to incandescence, the shield ablates, that is, it begins to decompose and erode. As the shield's surface deteriorates, a layer of gas is evolved continuously. This layer of gas insulates the spacecraft and carries away the excess heat.

Once a spacecraft with deployable parts attains airless space, it undergoes an insectlike metamorphosis. Freed from their cocoon when the launch shroud has been blown off, the solar cell paddles, radio antennas, and instrument booms unfold and unreel. As they deploy, they cause the spacecraft spin-rate to decrease. This despinning is the reverse of the skater's spinup maneuver caused by drawing in the arms and legs.

Solar cell paddles and other spacecraft appendages compete for "look angle." The solar cells must intercept sunlight; instruments need a clear view of space phenomena; and antennas must not be obstructed. The fair partition of the solid angle around each spacecraft is an important task in spacecraft design.

The Engineering Instrument Subsystem

Here we have the total of all housekeeping sensors. These sensors are the voltmeters, ammeters, thermometers, and other instruments that determine the status of the spacecraft.

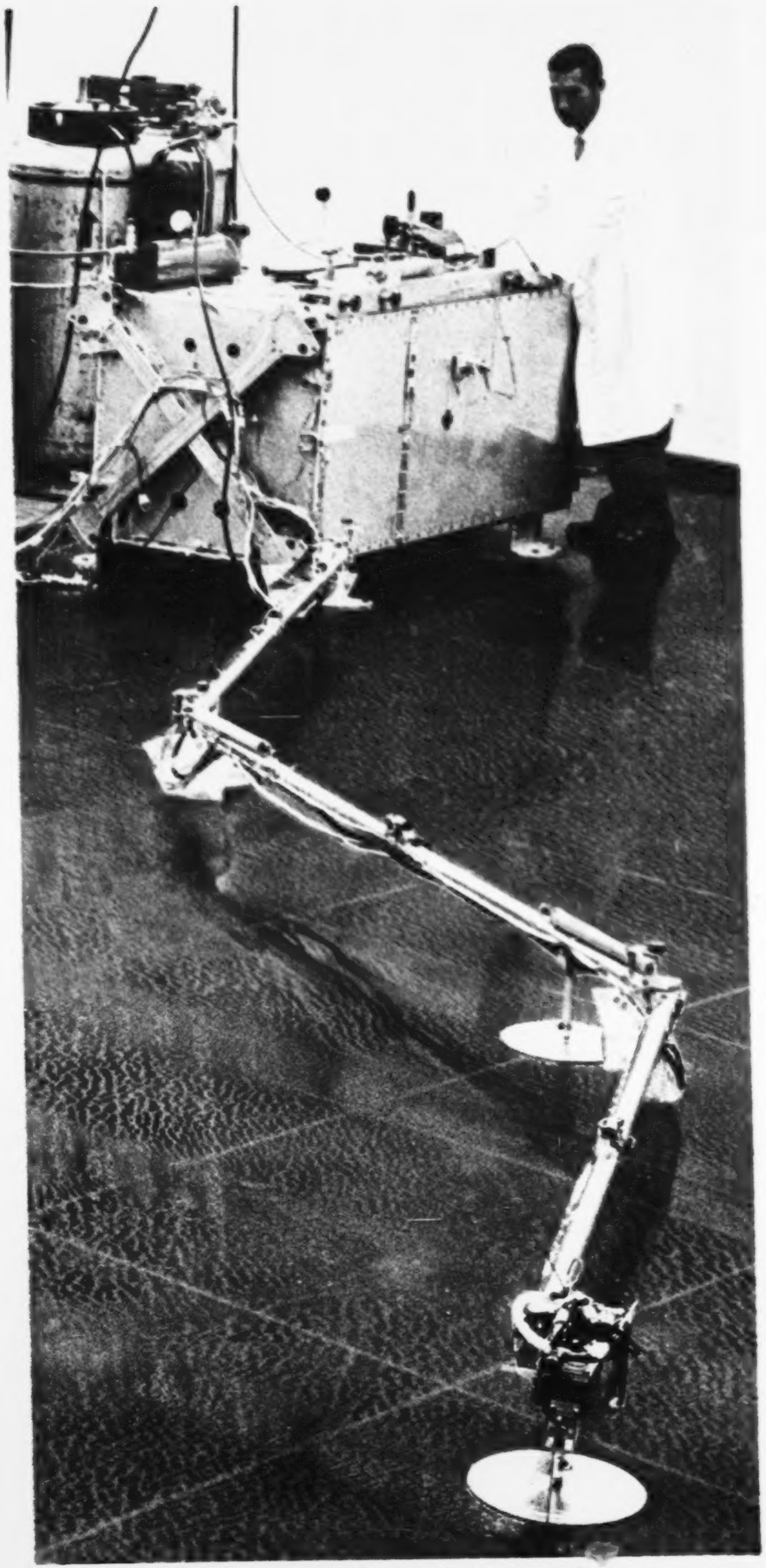
NASA Spacecraft Families

Below are listed the major NASA sounding rocket, satellite, and space probe families launched since NASA was created in October 1958.

Argo: A family of relatively large sounding rockets used by NASA (and others) for ionosphere and radio astronomy experiments. Launch weights vary between 10,000 and 14,000 pounds.

Ariel: A family of two scientific satellites built and launched by NASA, carrying experiments provided by Great Britain. Experiments focused on ionosphere and atmosphere research. Satellites were named after the "airy spirit" in Shakespeare's "The Tempest." Ariel I was launched on April 26, 1962; Ariel II, on March 27, 1964. They weighed 132 and 150 pounds, respectively.

Aerobee: A family of small sounding rockets used by NASA for experiments in the upper atmosphere. Also used for zero-g tests and rocket astronomy. The Aerobee-150 weighs about 1900 pounds at launch. There are several models.



6 *One of OGO's extendable booms being tested. Long booms help isolate sensitive instruments from the electromagnetic interference created in the spacecraft.*

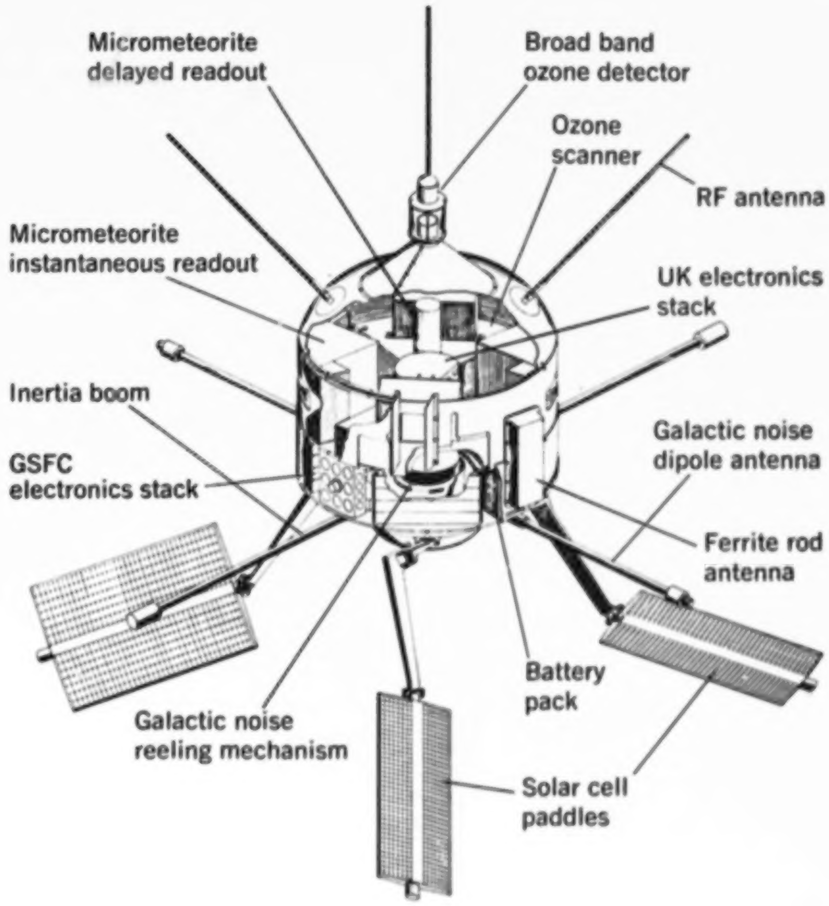
Astrobee: A series of large sounding rockets. The Astrobee-1500, used occasionally by NASA for tests, weighs about 11,500 pounds at launch.

ATS: NASA's family of multipurpose Applications Technology Satellites. The ATS satellites are intended to test new space instruments and satellite components, particularly those employed in synchronous orbit satellites.

ATS I	12-7-66 Tests of communication and meteorological instruments.
ATS II	4-6-67 Gravity-gradient experiment and more sensor experiments. Did not attain synchronous orbit.
ATS III	11-5-67 Meteorological, communication, and navigation experiments.

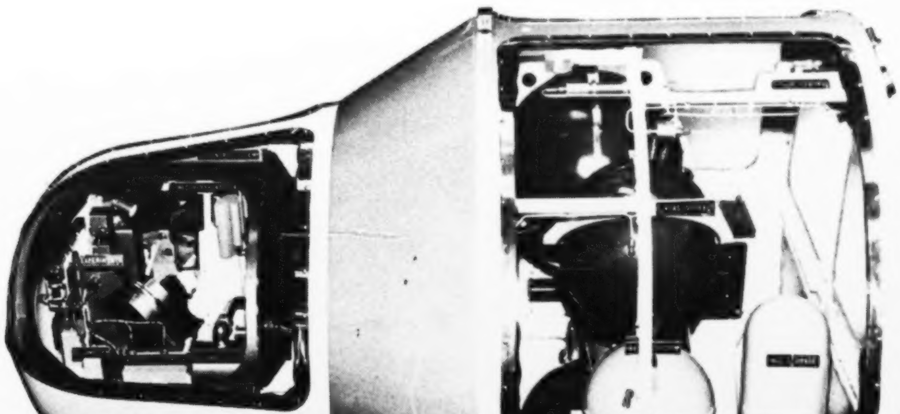
Biosatellite: Family of recoverable scientific satellites employed for testing the effects of weightlessness, radiation, and lack of the Earth's 24-hour rhythm on biological specimens. The first two Biosatellites each weighed about 950 pounds. Biosatellite I was launched on December 14, 1966, but its retrorocket did not fire, making recovery impossible. Biosatellite II, launched September 7, 1967, was recovered successfully.

Echo: A family of two passive NASA communication satellites. Once in orbit, these satellites were automatically inflated by a gas generator to become large spherical balloons 100 and 135 feet in diameter, respectively. These large metallized


Micrometeorite delayed readout
Broad band ozone detector
Ozone scanner
RF antenna
Micrometeorite instantaneous readout
UK electronics stack
Inertia boom
Galactic noise dipole antenna
GSFC electronics stack
Ferrite rod antenna
Battery pack
Galactic noise reeling mechanism
Solar cell paddles

7 *Ariel II. A satellite with cylindrical symmetry and numerous appendages.*

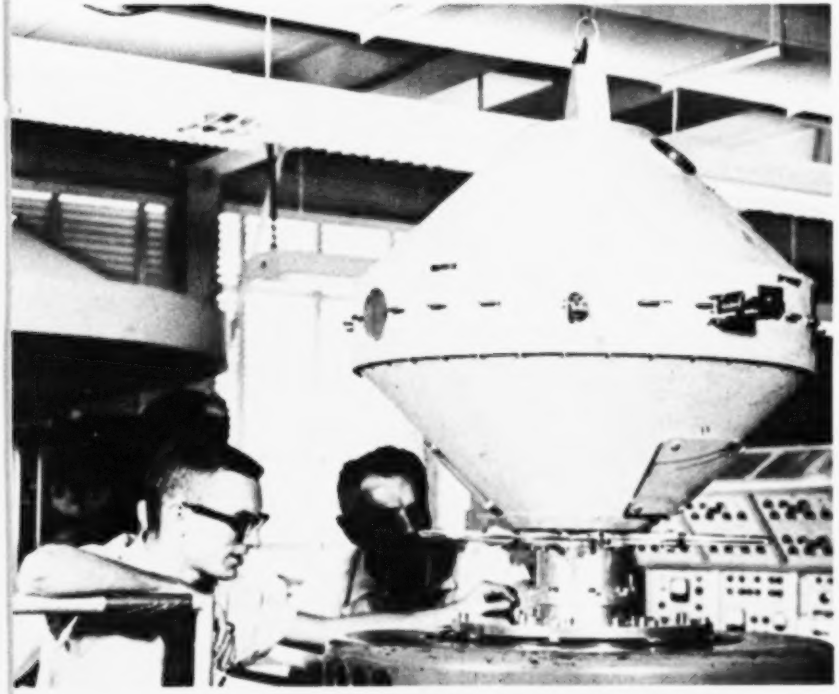
8 *Model of Biosatellite, showing primate experiment. Biosatellite is recoverable.*


BIOSATELLITE

balloons reflected radio signals between ground stations. Precision tracking of the Echo satellites also provided information about the density of the upper atmosphere. Echo I was launched August 12, 1960; Echo II, January 25, 1964. Both became wrinkled and lost their spherical shapes. Echo I reentered and burned in May 1968.

Explorer: A long series of scientific satellites that began before NASA was created. The Army Explorer I was the first U.S. satellite to be launched, on January 31, 1958. Explorers II, III, and IV were also Army satellites; the rest were launched by NASA. Explorers II and V were failures. As the following tabulation shows, the Explorer satellites have varied widely in design and purpose.

Explorer VI	8-7-59 Launched into highly elliptic orbit to explore magnetosphere. First use of solar paddles. Weight: 142 pounds.
Explorer VII	12-13-59 Solar physics studies and the measurement of space radiation. Weight: 92 pounds.
Explorer VIII	11-3-60 First of NASA's direct measurements satellites. Made significant measurements in ionosphere and upper atmosphere. Weight: 90 pounds.
Explorer IX	2-16-61 Small balloon satellite about 12 feet in diameter for measurements of air density. Weight: 80 pounds.
Explorer X	3-25-61 Launched into highly elliptical orbit to measure interplanetary phenomena. Returned only two days of data. Weight: 79 pounds.
Explorer XI	4-27-61 Designed to measure the distribution of cosmic gamma rays. Weight: 82 pounds.
Explorer XII	8-16-61 First of four NASA Energetic Particles Explorers, designed to measure the radiation belts, cosmic rays, solar wind, and magnetic fields. Weight: 83 pounds.
Explorer XIII	8-25-61 First of three NASA Micrometeoroid Explorers. Satellite was actually fourth stage of Scout rocket covered with micrometeoroid detectors. Orbit was too low; reentered in three days. Weight: 187 pounds.
Explorer XIV	10-2-62 Second Energetic Particles Explorer. Weight: 89 pounds.

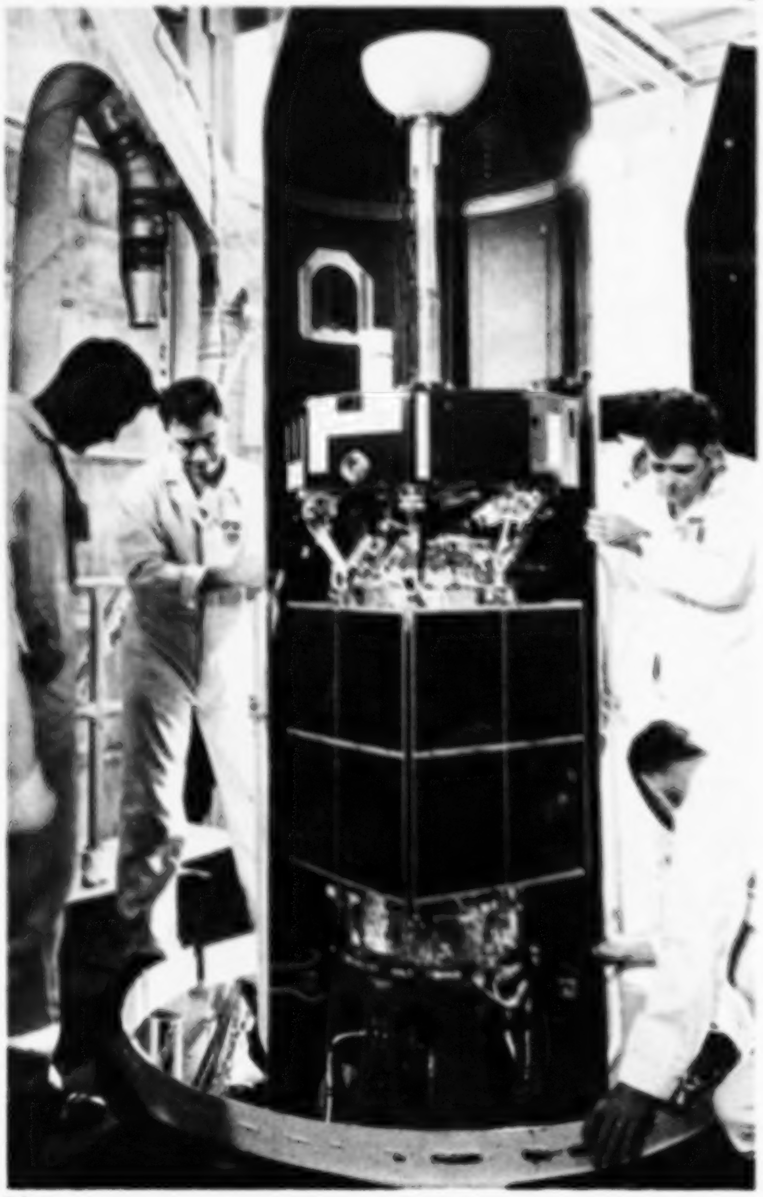


9 *Explorer VIII being tested on a vibration table before launch. Instruments for atmospheric and ionospheric research are located around the waist.*

10 *Explorer XXI, an IMP, is shown nested inside its launch shroud atop the Delta launch vehicle at Cape Kennedy. Solar cell paddles are retracted. Sphere on boom holds magnetometer.*

11 *The polyhedral Explorer XXV was built by the State University of Iowa for measurements in the Van Allen belt and polar regions. Solar cells are mounted on faces.*

10



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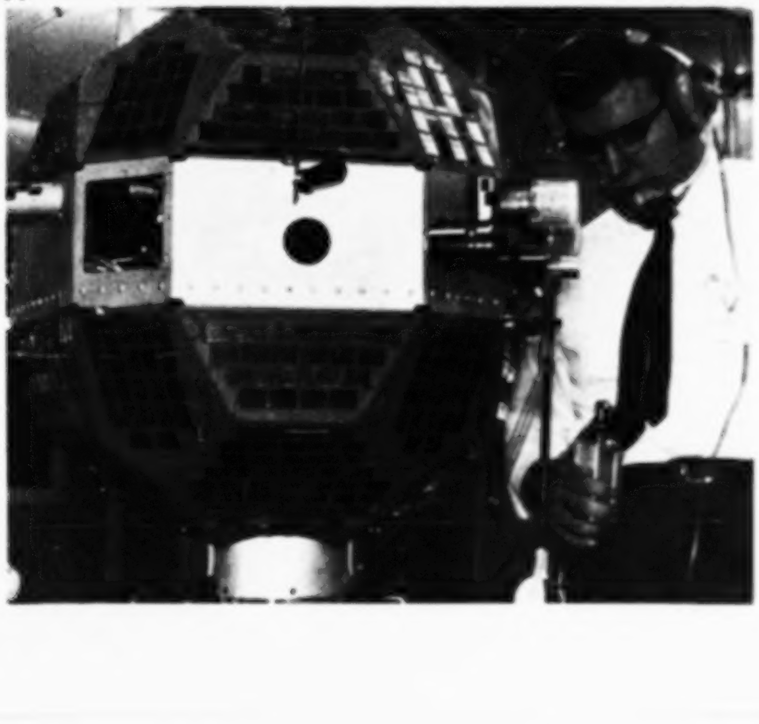
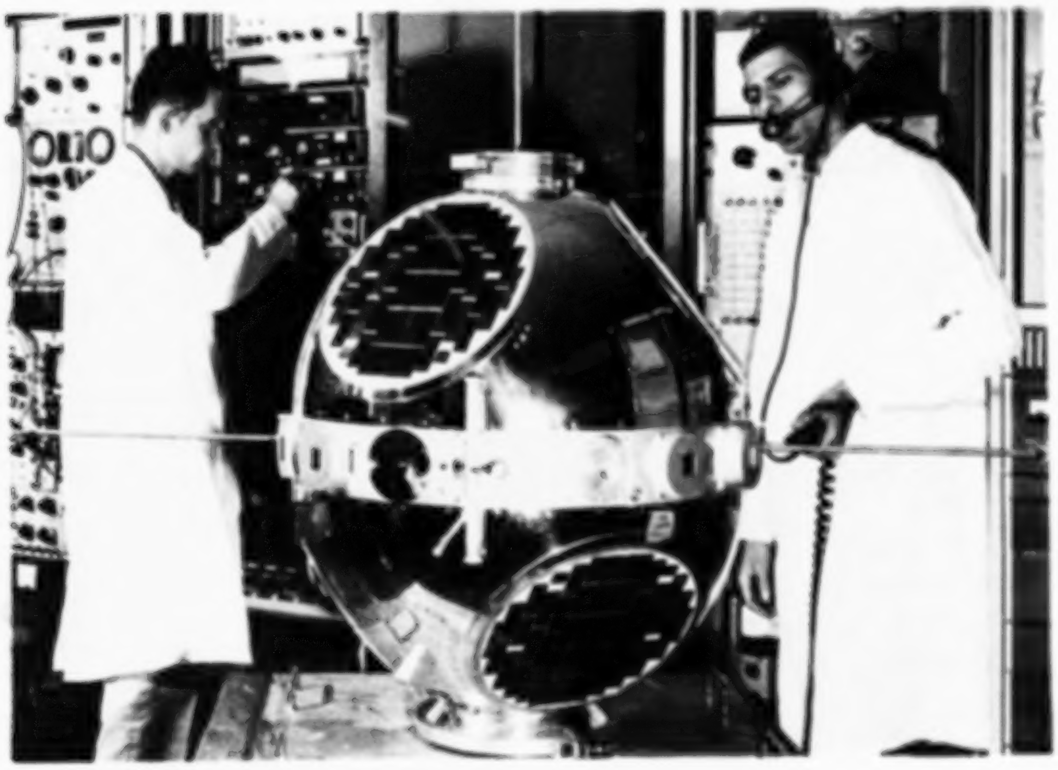


Explorer XV	10-27-62 Third Energetic Particles Explorer. Purpose was to study artificial radiation belt. Weight: 100 pounds.
Explorer XVI	12-16-62 Second Micrometeoroid Explorer. Weight: 159 pounds.
Explorer XVII	4-3-63 An Atmosphere Explorer, intended for the measurement of density, pressure, composition, and temperature directly. Weight: 405 pounds.
Explorer XVIII	11-27-63 First of the IMPs (Interplanetary Monitoring Platforms). Placed in a highly eccentric orbit to measure magnetic fields, plasma, and radiation. Weight: 138 pounds.
Explorer XIX	12-19-63 A balloon-type Air Density Explorer. Weight: 94 pounds.
Explorer XX	8-25-64 An Ionosphere Explorer. This satellite was a topside sounder that sent radio pulses down into the ionosphere and listened for echos. Weight: 98 pounds.
Explorer XXI	10-4-64 Second IMP. Weight: 135 pounds.
Explorer XXII	10-10-64 First of NASA's Beacon Explorers. Primarily a radio beacon for studying radio propagation in the ionosphere. Weight: 116 pounds.
Explorer XXIII	11-6-64 Third Micrometeoroid Explorer. Weight: 295 pounds
Explorer XXIV	11-21-64 Another balloon-type Air Density Explorer. Weight: 19 pounds.
Explorer XXV	11-21-64 A satellite to monitor the radiation belt. One of the Injun series built by the State University of

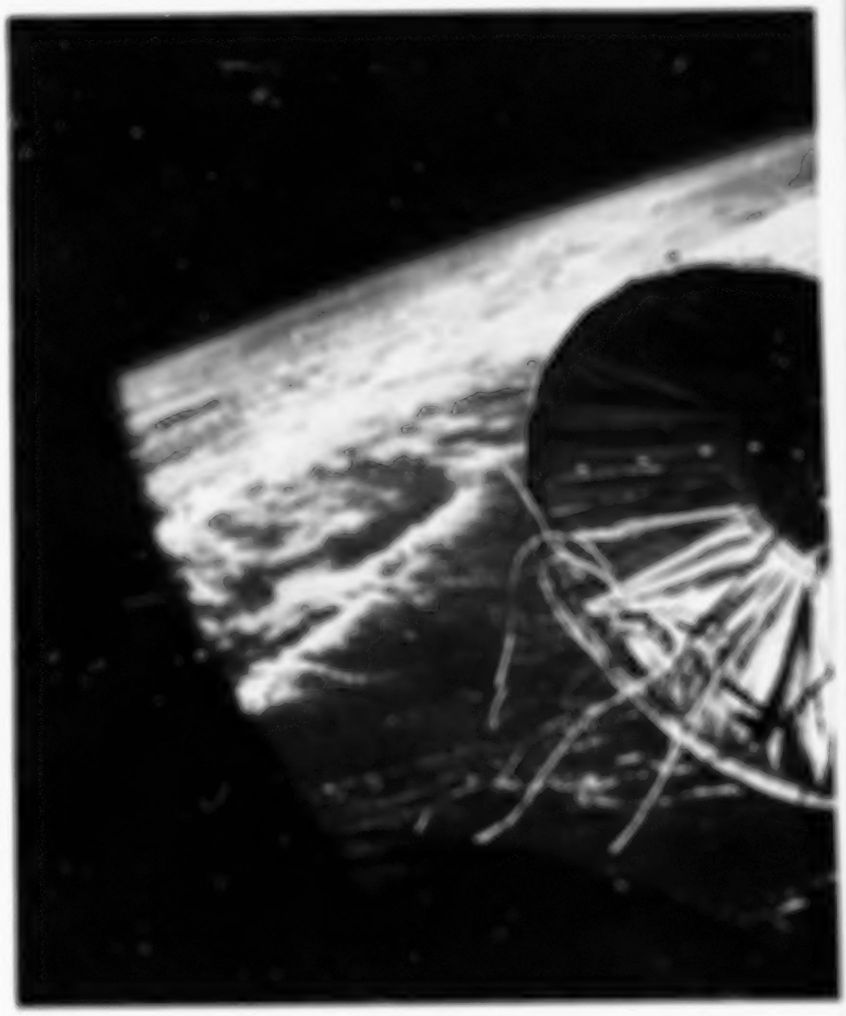
	Iowa. Launched with Explorer XXIV for NASA's first dual launch. Weight: 90 pounds.
Explorer XXVI	12-21-64 Last of four Energetic Particles Explorers. Weight: 101 pounds.
Explorer XXVII	4-29-65 NASA's second Beacon Explorer. Weight: 134 pounds.
Explorer XXVIII	5-29-65 Third IMP. Weight: 130 pounds.
Explorer XXIX	11-6-65 A Geodetic Explorer, called Geos for short. Carried radio beacons and flashing light to enhance tracking. Weight: 385 pounds.
Explorer XXX	11-19-65 A Solar Explorer for monitoring solar radiation during the International Year of the Quiet Sun (IQSY). Weight: 125 pounds.
Explorer XXXI	11-29-65 A Direct Measurement Explorer for ionospheric studies. Weight: 218 pounds.
Explorer XXXII	5-25-66 An Atmosphere Explorer similar to Explorer XVII. Weight: 490 pounds.
Explorer XXXIII	7-1-66 An Anchored IMP with a possibility of achieving a lunar orbit. Did not attain lunar orbit; in orbit around the Earth. Weight: 207 pounds.
Explorer XXXIV	5-24-67 Fifth IMP. Weight: 163 pounds.
Explorer XXXV	7-19-67 First Anchored IMP to achieve orbit around the Moon. Weight: 230 pounds.
Explorer XXXVI	1-11-68 Second Geodetic Explorer.
Explorer XXXVII	3-5-68 Second Solar Explorer.



12 *Explorer XXX during ground tests. Solar cells are mounted on the flat faces.*

Gemini: The second series of manned NASA Earth satellites. Two astronauts occupied each Gemini capsule, hence the series name. The prime purpose of the Gemini flights was to check out equipment and techniques to be used during the Apollo missions to the Moon. During the Gemini Program, NASA performed the first rendezvous experiments and the first extravehicular activities (walks in space). Gemini capsule weights varied between 7000 and 14,000 pounds.

Gemini I	4-8-64 Unmanned orbital test flight.
Gemini II	1-19-65 Unmanned suborbital test flight.
Gemini III	3-23-65 Three-revolution flight. Astronauts: Grissom and Young.
Gemini IV	6-3-65 62 revolutions, roughly four days. First U.S. walk in space. Astronauts: McDivitt and White.
Gemini V	8-21-65 120 revolutions, roughly eight days. First extended U.S. manned space flight. Rendezvous maneuvers. Astronauts: Cooper and Conrad.
Gemini VII	12-4-65 206 revolutions, roughly two weeks. Rendezvoused with Gemini VI-A. Astronauts: Borman and Lovell.
Gemini VI-A	12-15-65 15 revolutions, a little over one day. Rendezvoused with Gemini VII. (Gemini VI was cancelled 10-25-65 when target vehicle failed to attain orbit.) Astronauts: Schirra and Stafford.
Gemini VIII	3-16-66 6.5 revolutions, 10.7 hours. Reentered early because of malfunctioning spacecraft thruster. Astronauts: Armstrong and Scott. First docking in space.
Gemini IX-A	6-3-66 45 revolutions, about three days. Rendezvous tests with unmanned target. Walk in space. Astronauts: Stafford and Cernan. (Gemini IX was cancelled May 17, 1966 when target vehicle failed to orbit).
Gemini X	7-18-66 43 revolutions, roughly three days. More rendezvous experiments. Astronauts: Young and Collins.
Gemini XI	9-12-66 44 revolutions, about three days. High apogee flight to 853 miles. Rendezvous, docking, extravehicular activity, tether evaluation. Astronauts: Conrad and Gordon.
Gemini XII	11-11-66 59 revolutions, about four days. Demonstrated automatic reentry. Further docking, rendezvous, and extravehicular experiments. Astronauts: Lovell and Aldrin.



Iris: Family of small sounding rockets used for upper atmosphere experiments. Launch weight: about 1300 pounds.

Javelin: Family of sounding rockets based on Argo rocket.

Journeyman: Large NASA sounding rocket. Launch weight: about 14,000 pounds.

Lunar Orbiter: Series of five lunar probes placed in orbit around the Moon. Purpose: reconnoiter

13 *One Gemini spacecraft is seen through the window of another during the flights of Gemini VI-A and Gemini VII in December 1965.*

possible landing sites for Apollo astronauts. Took large number of high quality pictures of the lunar surface. Weights: 850-860 pounds.

Lunar Orbiter I	8-10-66 First U.S. spacecraft in lunar orbit. Returned 207 frames of pictures (sets of two each).
Lunar Orbiter II	11-6-66 Returned 211 frames of pictures.
Lunar Orbiter III	2-5-67 Returned 182 frames of pictures.
Lunar Orbiter IV	5-4-67 Returned 163 frames of pictures. Eighty percent of far side photographed by Orbiters I to IV.
Lunar Orbiter V	8-1-67 Covered five Apollo landing sites and 36 scientific interest sites; completed far side high altitude coverage; full view of Earth in full phase. Returned 212 frames of pictures.

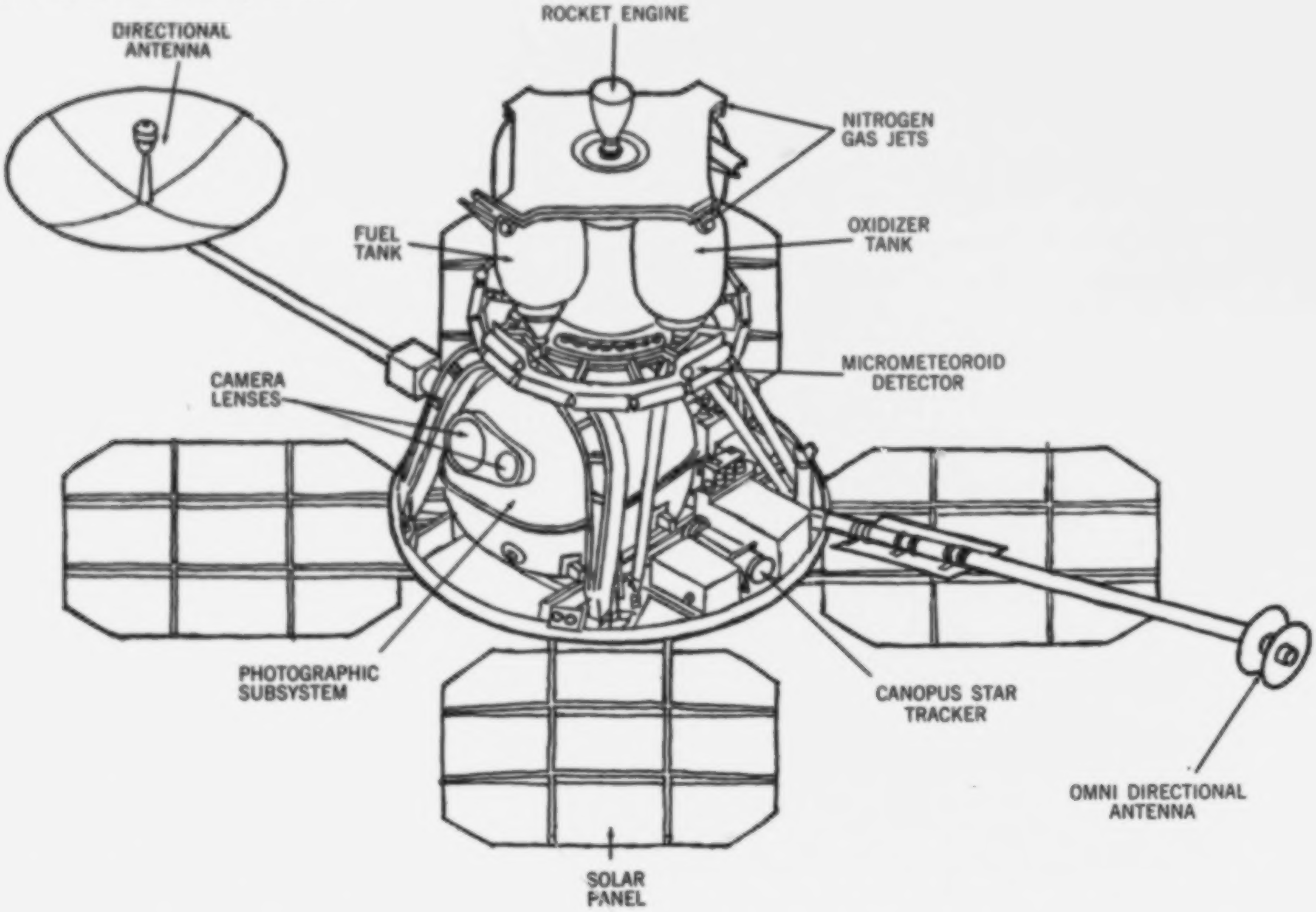
Mariner: A family of planetary probes designed to fly by Mars and Venus, making scientific measurements in interplanetary space on the way. In the vicinity of a planet, the Mariner probes scanned the planet with instruments and carried out radio occultation experiments.

Mariner I	7-22-62 Venus probe. A launch failure, destroyed by range safety officer.
Mariner II	8-27-62 First flyby of Venus. Made magnetic and atmospheric studies near planet. Encountered Venus December 14, 1962. Weight 449 pounds.
Mariner III	11-5-64 Mars probe. Launch shroud failed to eject.
Mariner IV	11-28-64 First flyby of Mars. Took first close-up pictures of Mars' cratered surface. Encountered Mars July 14, 1965. Weight: 575 pounds.
Mariner V	6-14-67 Second U.S. flyby of Venus. Made measurements of Venus' ionosphere, magnetosphere, and atmosphere. Encountered Venus October 19, 1967. Weight 542 pounds.

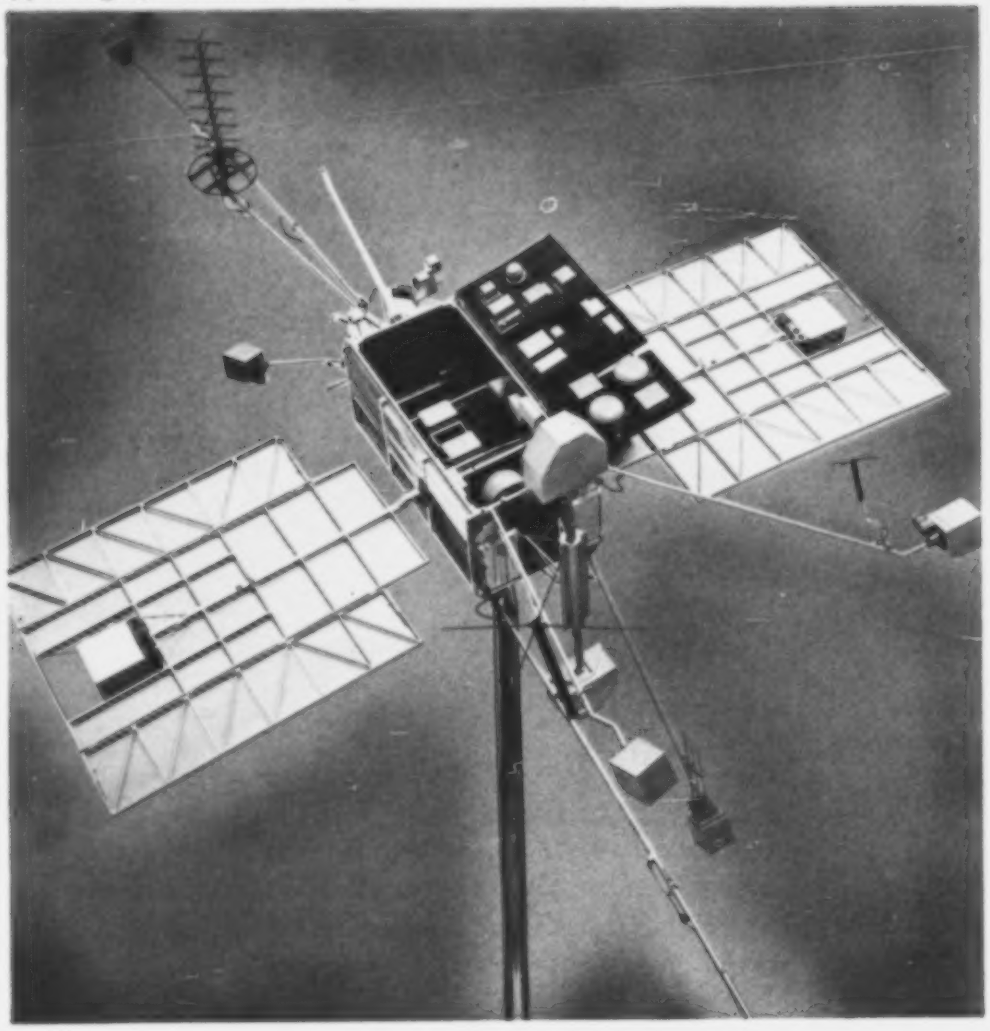
Mercury: The first U.S. manned spacecraft. The Mercury capsule supported only one astronaut in comparison to two in Gemini. The primary purpose of the flights was to demonstrate that man could not only survive in space but could perform useful tasks. Capsule weights ranged from 2300 to 3033 pounds.

Mercury-Atlas I	7-29-60 Unmanned test of structure and reentry heat protection shield.
Mercury-Redstone I	11-21-60 Unmanned test. Launch abort.
Mercury-Redstone IA	12-19-60 Unmanned 235-mile test flight.
Mercury-Redstone II	1-31-61 Suborbital flight with primate aboard.
Mercury-Atlas II	2-21-61 Unmanned suborbital flight.
Mercury-Redstone III (Freedom 7)	5-5-61 Manned suborbital flight. Astronaut: Shepard.
Mercury-Redstone IV (Liberty Bell 7)	7-21-61 Manned suborbital flight. Astronaut: Grissom.
Mercury-Atlas IV	9-13-61 Unmanned, single-orbit flight, about 1.5 hours long.
Mercury-Atlas V	11-29-61 Three-orbit flight, about 4.5 hours long, with chimp Enos aboard.
Mercury-Atlas VI (Friendship 7)	2-20-62 Three-orbit, manned flight, roughly five hours long. First U.S. orbital flight. Astronaut: Glenn.

14 *The Lunar Orbiter spacecraft.*


DIRECTIONAL ANTENNA
ROCKET ENGINE
NITROGEN GAS JETS
FUEL TANK
OXIDIZER TANK
MICROMETEOROID DETECTOR
CAMERA LENSES
PHOTOGRAPHIC SUBSYSTEM
CANOPUS STAR TRACKER
OMNI DIRECTIONAL ANTENNA
SOLAR PANEL

15 *Model of OGO showing solar panels, numerous appendages, and boxlike body with cover door open.*



Mercury-Atlas VII (Aurora 7)	5-24-62 Three orbits, roughly five hours. Astronaut: Carpenter.
Mercury-Atlas VIII (Sigma 7)	10-3-62 Six orbits, a little over nine hours. Astronaut: Schirra.
Mercury-Atlas IX (Faith 7)	5-15-63 22 orbits, lasting 34 hours and 20 minutes. Astronaut: Cooper.

Nike: A large family of sounding rockets, including the Nike-Asp, the Nike-Cajun, and the Nike-Tomahawk. These are all small rockets with launch weights generally under a ton. NASA has fired hundreds of Nike-class sounding rockets during its ionosphere and upper atmosphere research programs.

Nimbus: A family of large, research-and-development, meteorological satellites. The Nimbus satellites have tested a number of cameras and infrared instruments for operational weather satellite programs. Nimbus I was launched August 28, 1964 and weighed 830 pounds. This satellite provided many thousands of high quality cloud-cover pictures. It was the first weather satellite with three-axis stabilization. Nimbus II, weighing 912 pounds, was launched May 15, 1966. Besides weather pictures, it returned infrared, night-cloud-cover pictures.

OAO: NASA's Orbiting Astronomical Observatory. The OAOs are large sophisticated satellites for studying the stars in the ultraviolet region of the spectrum and carrying out associated experiments in space science. OAO I was launched April 8, 1966 and weighed 3900 pounds. Spacecraft systems anomalies developed on the second day and no scientific results were obtained.

OGO: NASA has built a family of Orbiting Geophysical Observatories. Each of these large satellites can carry twenty or more experiments in the fields of geophysics, space physics, and astronomy. Like the other Observatories, OGOs are large and relatively sophisticated, weighing between 1000 and 1300 pounds. Some of the OGOs are injected into polar orbits and are called POGOs. Those in high eccentric orbits are called EGOs.

OGO I	9-5-64 In eccentric orbit. Two booms failed to deploy, blocking a horizon sensor. Consequently, OGO I could not stabilize facing the Earth. Many experiments still returned good data.
OGO II	10-14-65 This OGO was placed in a polar orbit. The attitude control gas supply was exhausted prematurely due to a sensor problem. Most experiments were successful.
OGO III	6-7-66 In eccentric orbit. Maintained Earth-stabilization for more than six weeks.
OGO IV	7-28-67 In polar orbit. Eighteen experiments returning data.
OGO V	3-4-68 Twenty-four experiments operating.

OSO: The Orbiting Solar Observatories are the smallest of the Observatory class and carry fewer experiments. Weights vary between 450 and 650 pounds. Some experiments are located in the spinning wheel section; others are in the sail, which is kept pointed at the Sun.

OSO I	3-7-62 Carried a dozen solar physics experiments, including an ultraviolet spectrometer aimed at the Sun.
OSO II	2-3-65 Instruments included a coronagraph and ultraviolet spectroheliograph.
OSO III	3-8-67 Carried a solar monochromator and spectrometer.
OSO IV	10-18-67 Continuation and expansion of previous experiments.

Pageos: A balloon-type, passive geodetic satellite. Observed with optical instruments. Pageos was launched on June 24, 1966. Weight: 244 pounds.

Pegasus: The three Pegasus satellites have sometimes been called Micrometeoroid Explorers, but they are much larger than any Explorer-class satellite, weighing about 23,000 pounds each. These satellites were orbited as byproducts of the Saturn I launch tests. Each was a Saturn S-IV upper stage which carried a large folded array of capacitor-type micrometeoroid detectors, deployed once orbit was attained.

Pegasus I	2-16-65
Pegasus II	5-25-65
Pegasus III	7-30-65

Pioneer: The first five Pioneer probes were aimed to fly in the general direction of the Moon, but not to hit it. They either fell back to Earth, or continued on into solar orbit. The second series, beginning with Pioneer VI, is aimed at deep-space exploration. These later Pioneers carry magnetometers, solar wind instrumentation, radiation counters, etc.

Pioneer I	10-11-58 Reached altitude of 70,000 miles. Returned data on Van Allen belts. Weight: about 84 pounds.
Pioneer II	11-8-58 A launch failure.
Pioneer III	12-6-58 Reached an altitude of over 63,500 miles. Helped map the magnetosphere. Weight: 13 pounds.
Pioneer IV	3-3-59 In solar orbit; passed Moon at the distance of 37,300 miles. Weight: 13.4 pounds.
Pioneer V	3-11-60 In solar orbit. Returned data out to 22,000,000 miles. Weight: 95 pounds.
Pioneer VI	12-16-65 First of the new series. In solar orbit. Weight: 140 pounds.

Pioneer VII	8-17-66 In solar orbit. Weight: 140 pounds.
Pioneer VIII	12-13-67 Weight: 145 pounds

Rangers: The first two Rangers were intended to test out techniques to be used on lunar and planetary spacecraft as well as measure the particles and fields present in interplanetary space. They were to be aimed in the general direction of the Moon. The next three Rangers were to "rough land" a seismometer package on the lunar surface. The final four Rangers were designed to take close-up pictures of the lunar surface before crash landing on it, providing data for planning the lunar landing of Apollo astronauts. The Rangers weighed between 675 and 810 pounds.

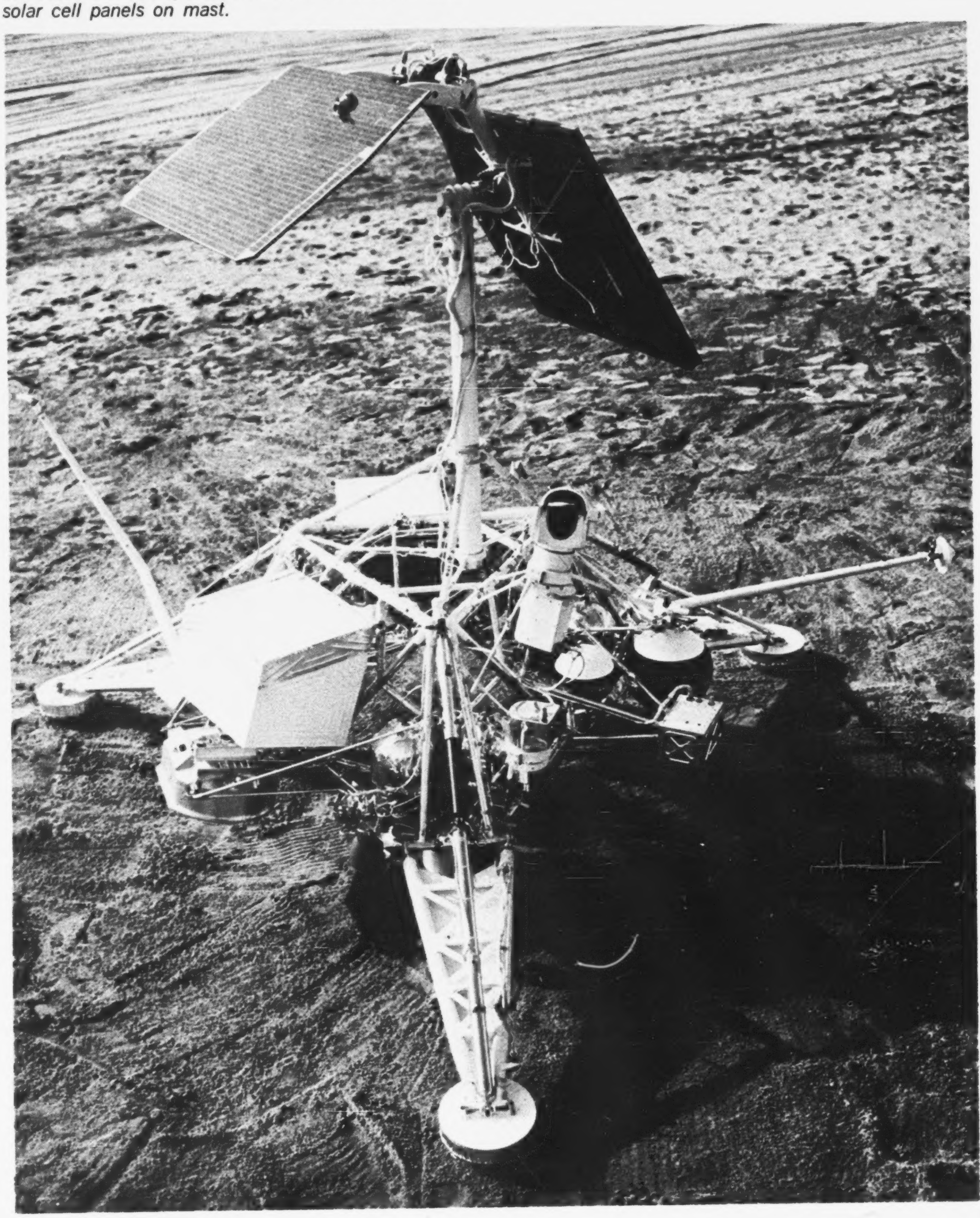
Ranger I	8-23-61 Launched into Earth orbit.
Ranger II	11-18-61 Same as Ranger I.
Ranger III	1-26-62 In solar orbit; passed Moon at about 22,862 miles.
Ranger IV	4-23-62 Hit Moon. Timer failure prevented experiment operation.
Ranger V	10-18-62 In solar orbit; missed Moon by 450 miles.
Ranger VI	1-30-64 Hit Moon; but camera failed.
Ranger VII	7-28-64 Hit Moon; returned 4316 pictures.
Ranger VIII	2-17-65 Hit Moon; took 7137 pictures.
Ranger IX	3-21-65 Hit Moon; took 5814 pictures.

Relay: A family of two active experimental communication satellites. Relay I, launched December 13, 1962, was able to handle twelve simultaneous two-way telephone conversations or one television channel. Relay II was an improved version, launched on January 21, 1964. They weighed 172 and 183 pounds, respectively.

Surveyor: A series of seven soft-landing lunar probes built to reconnoiter the Moon's surface in preparation for the Apollo manned landing. The first Surveyors were primarily picture-taking spacecraft. Later models added experiments in soil mechanics and analyzed the surface composition. Weights varied between 596 and 630 pounds at lunar landing.

Surveyor I	5-30-66 Soft-landed on Moon. Sent back over 11,338 photos.
Surveyor II	9-20-66 Hit Moon, but one of the three retrorockets failed during mid-course maneuver; soft landing not possible.
Surveyor III	4-17-67 Successful soft landing. Took 6,315 photos. Soil sampler experiment showed lunar surface similar to damp sand in strength.
Surveyor IV	7-14-67 Hit Moon; but communications lost 2.5 minutes before touchdown.

16 *The Surveyor soft lunar lander. Retrorocket slowed the descent of the spacecraft before touchdown. Note solar cell panels on mast.*



Surveyor V	9-8-67 Sent over 19,000 pictures of lunar surface. Alpha-scattering experiment showed surface composition similar to basalt.
Surveyor VI	11-7-67 Sent more than 30,000 photos. Alpha-scattering experiment again showed basalt.
Surveyor VII	1-7-68 Landed in lunar highlands. Took some 21,000 pictures. Alpha-scattering experiment showed highlands to differ appreciably from maria in composition.

Syncom: Family of three experimental, active, synchronous-orbit communication satellites. The Syncoms were first injected into highly elliptic orbits. Near apogee, a rocket fired and placed them in equatorial synchronous (stationary) orbits. An onboard gas-jet propulsion unit was required to maintain their orbital positions. Weight: about 85 pounds each.

Syncom I	2-14-63 In nearly synchronous orbit; but communications failed just after onboard rocket fired.
Syncom II	7-26-63 First satellite placed in synchronous orbit. Many very successful intercontinental communication experiments.
Syncom III	8-19-64 First stationary Earth satellite. Demonstrated the practicality and effectiveness of stationary, active communication satellites.

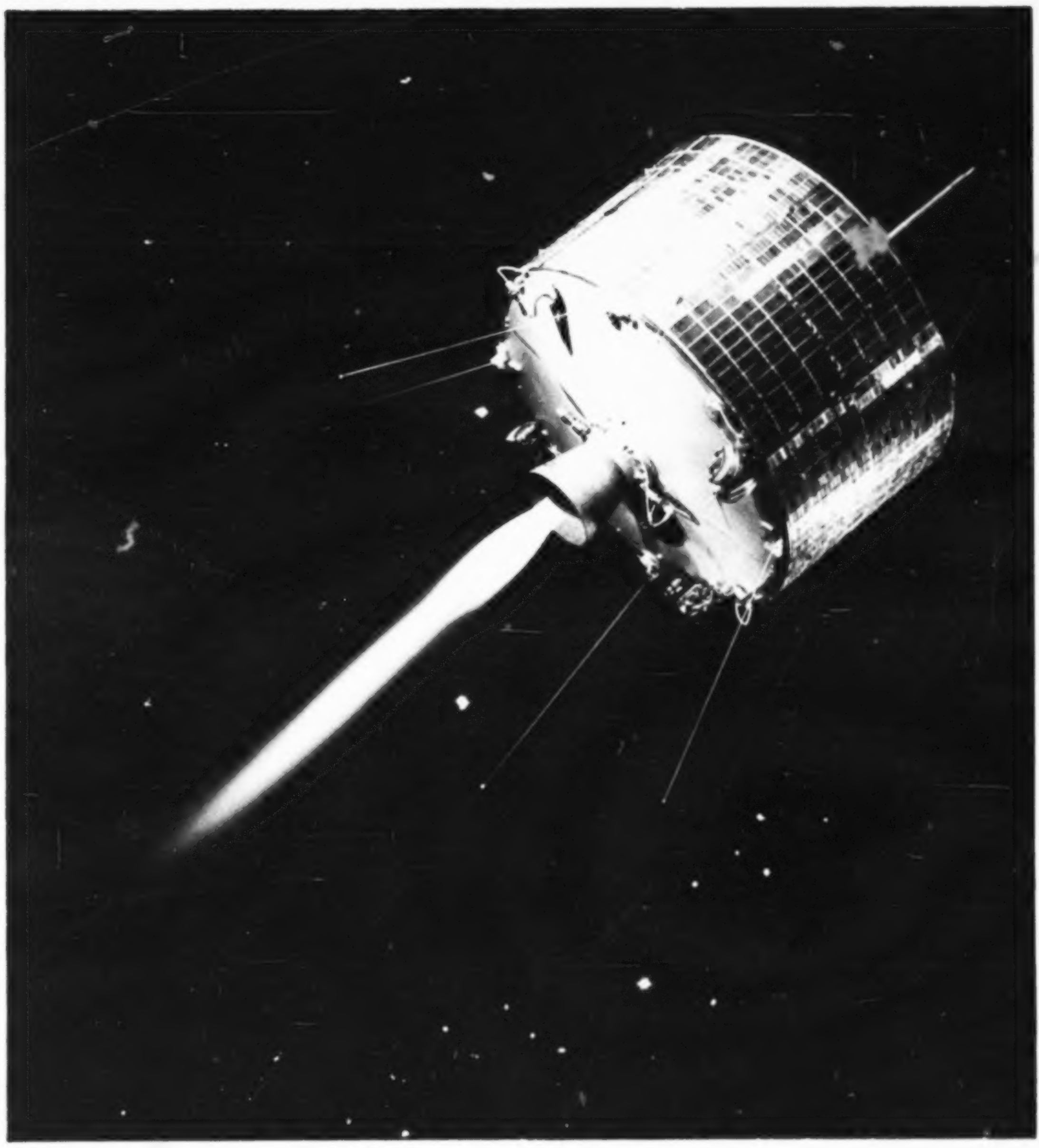
TIROS: A long, successful series of experimental weather satellites. The TIROS series demonstrated conclusively that satellite cloud-cover and infrared pictures would be useful in improving the accuracy of weather forecasting. The TIROS successes formed the basis for the TIROS Operational Satellite (TOS), which the Environmental Science Services Administration calls Environmental Survey Satellites or ESSAs. The TIROS satellites are hat-box-shaped and weigh between 260 and 300 pounds. All TIROS satellites were spin-stabilized.

TIROS I	4-1-60 23,000 weather pictures.
TIROS II	11-23-60 36,000 weather pictures.
TIROS III	7-12-61 Over 35,000 weather pictures.
TIROS IV	2-8-62 Over 32,500 weather pictures.
TIROS V	6-19-62 Over 58,000 weather pictures.
TIROS VI	9-18-62 Over 66,600 weather pictures.
TIROS VII	6-19-63 Still operating. Over 125,000 weather pictures so far.
TIROS VIII	12-21-63 Still active. Over 100,000 weather pictures so far. First APT (Automatic Picture Transmission) equipment.

TIROS IX	1-22-65 Established feasibility of cartwheel configuration for operational weather satellites.
TIROS X	7-2-65 Placed in Sun-synchronous orbit.

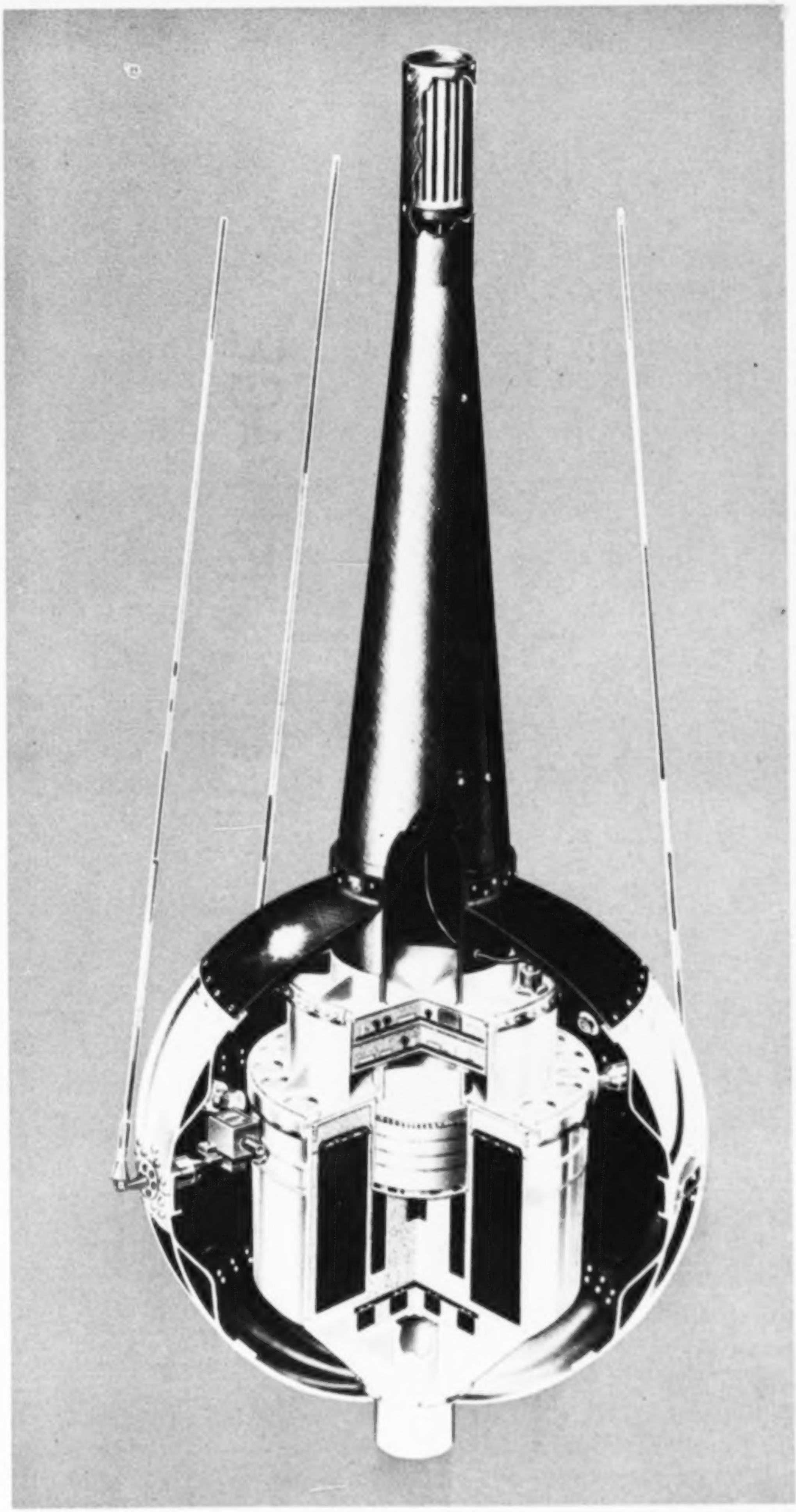
Vanguard: A family of three scientific satellites. Begun in 1955, the Vanguard satellite program planned to launch at least one small artificial satellite during the International Geophysical Year. Vanguard I was launched on March 17, 1958, under the auspices of the U.S. Navy. The Project was transferred to NASA in October 1958.

Vanguard II	2-17-59 Launched to televise cloud cover, but excessive wobble degraded data. Weight: 22 pounds.
Vanguard III	9-18-59 Carried micrometeoroid detectors, radiation detectors, a magnetometer, and solar X-ray detectors. Weight: 100 pounds.



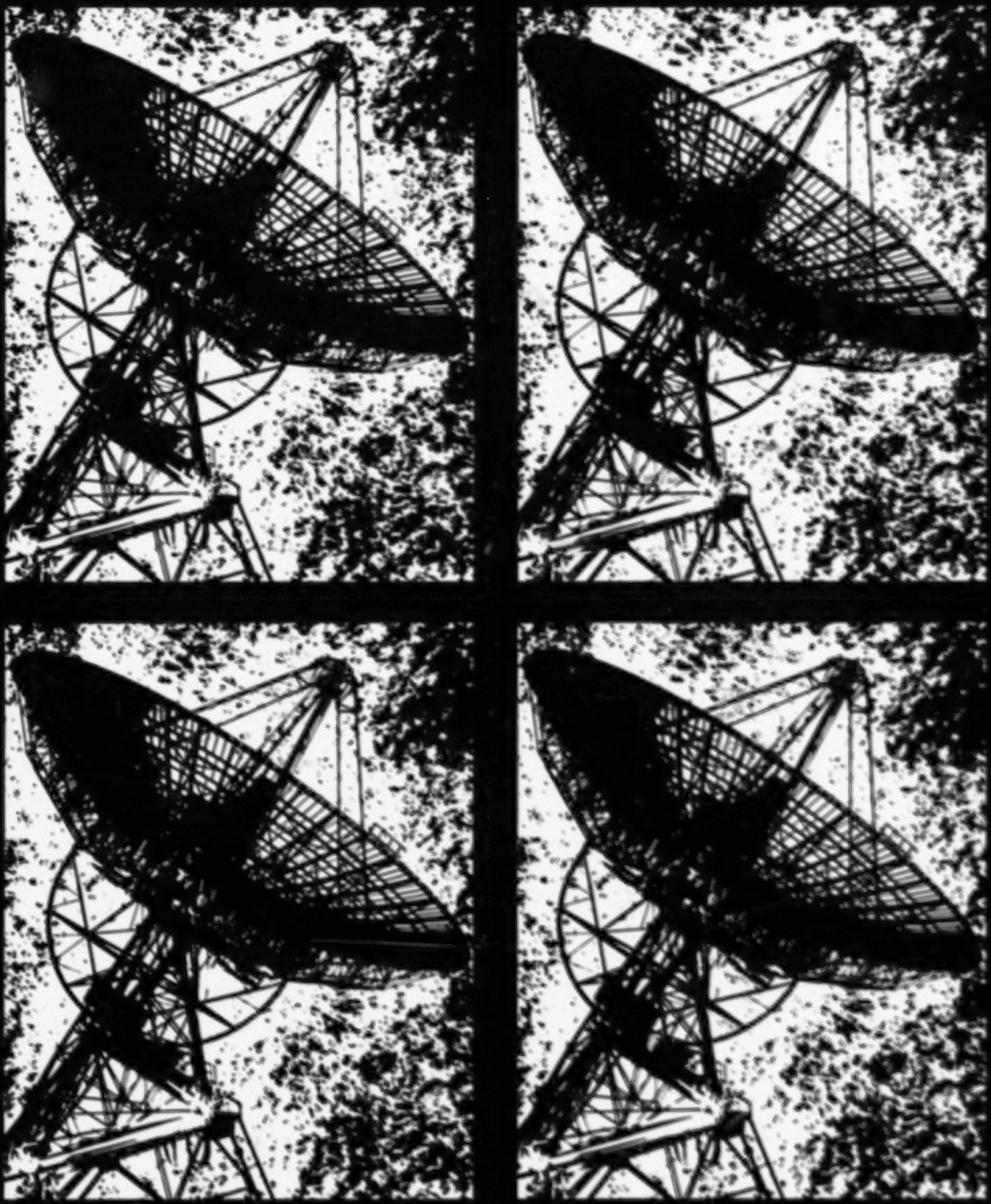
17 *Syncom, a synchronous communication satellite; weight approximately 55 pounds. Solar cells are mounted on the circumference of the cylinder.*

18 *Vanguard III. The conical boom on top isolated the magnetometer from the rest of the spacecraft.*



America In Space | The First Decade

Spacecraft Tracking



National Aeronautics and Space Administration

America
In
Space:
The
First
Decade

This is one of a series of booklets published on the occasion of the 10th Anniversary of the National Aeronautics and Space Administration.
These publications are not intended to be comprehensive history, nor do they deal with all the facets of NASA's aeronautical and space activities. Rather they are overviews of some important activities, programs and events written for the layman in terms of the several science disciplines.

Each of these subjects is treated in more depth in other NASA publications and in scientific journals.

1 October 1968

Titles in this series include:

I Space Physics and Astronomy
II Exploring the Moon and Planets
III Putting Satellites to Work
IV NASA Spacecraft
V Spacecraft Tracking
VI Linking Man and Spacecraft
VII Man in Space

Others are in preparation. Topics include:

Propulsion
Spacecraft Power
Space Life Sciences
Aeronautics
Space Age By-products
Materials

SPACECRAFT TRACKING

by William R. Corliss

National Aeronautics and Space Administration, Washington, D.C. 20546

Introduction

Spacecraft tracking involves much more than merely finding and following each spacecraft as it traces its own unique course through space. The location of the spacecraft must be accurately determined so that the scientific data it is acquiring can be matched to that position. Also, the spacecraft's path is precisely monitored because small perturbations yield valuable information about changes in the gravity field, variations in atmospheric density, to name but two.

"Spacecraft Tracking" deals with this precise locating of spacecraft dispatched from Earth. Tracking is difficult to separate from spacecraft communications in the sense that NASA's three worldwide ground-based networks perform both functions. Most NASA network stations possess antennas that can both track and acquire spacecraft data. Despite this dual capability of NASA hardware, spacecraft communications—a subject dealing with the transfer of information to and from spacecraft and the Earth—has a different theoretical background. Because of this distinction, spacecraft communications is treated in another booklet in this series: "Linking Man and Spacecraft."

Gerald M. Truszynski
Associate Administrator for
Tracking and Data Acquisition

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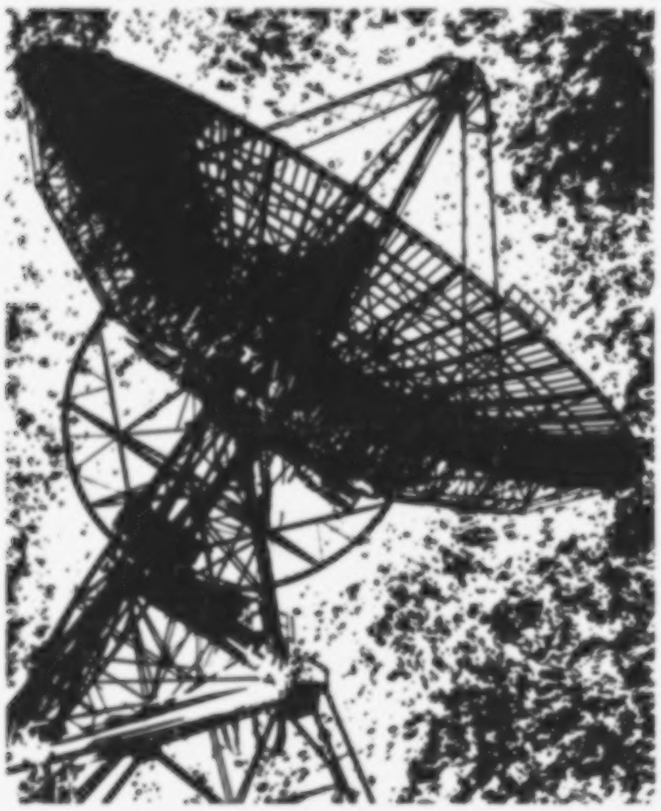


Spacecraft Tracking

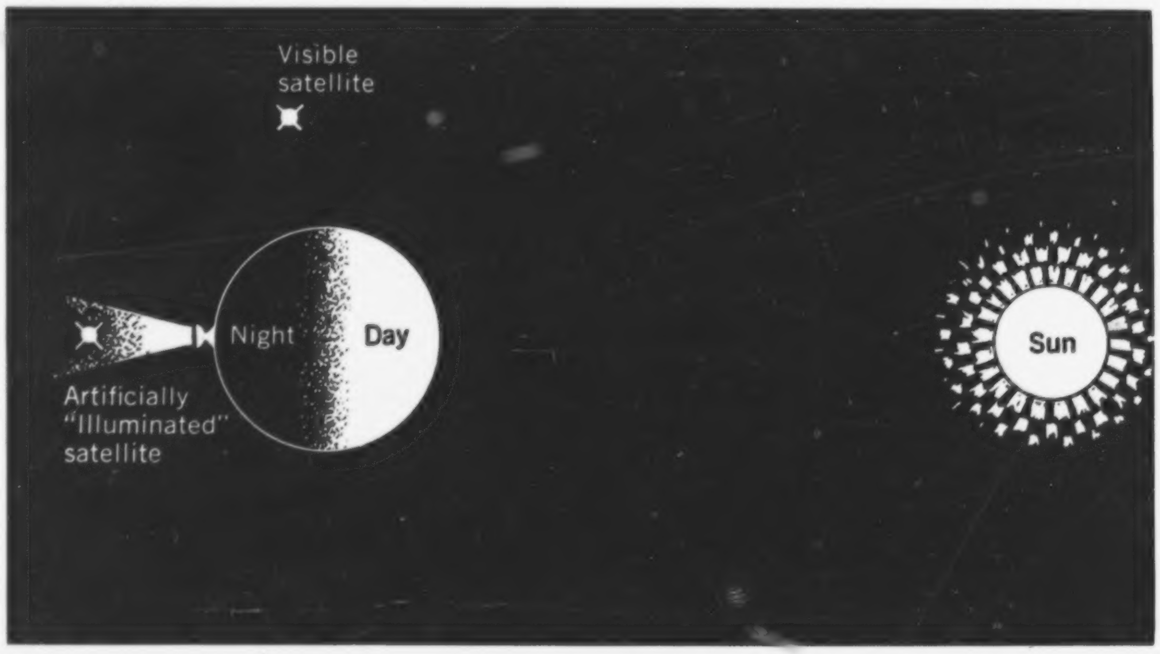
The Celestial Haystack

Finding and following spacecraft as they crisscross the sky overhead is called tracking. In 1958, when the number of satellites in orbit could be counted on the fingers of one hand, the major tracking problem was finding the tiny satellites in the immensity of space. Between 1958 and 1968, however, almost 800 artificial satellites and space probes were launched. Today's tracking problem is not finding spacecraft, rather it is sorting them out and coping with the heavy traffic flow. Even more traffic is caused by the growing stream of space debris—pieces of defunct rockets, exploded spacecraft, the flotsam and jetsam of space exploration. Well over 1000 pieces of space hardware are in orbit at any one moment. Tracking spacecraft is akin to keeping tabs on all the aircraft around a busy airport, except that the targets are much higher and travel much faster.

Remember those exciting days when the first satellites were being shot into orbit? In the early evening, people would rush outdoors to see the bigger ones—still illuminated by the Sun below the horizon—cruise across the background of the stars. Many satellites are still tracked by reflected sunlight, but only when the Sun and satellite are in the right positions. When we wish to track spacecraft 24 hours a day we must make them visible artificially. We cannot duplicate the Sun but we can shine radar, laser, and/or radio beams on them and detect the echoes and reflections.

The easy way to track spacecraft, though, is to make them announce their presence themselves with a beacon or transponder. The great majority of satellites and space probes carry radio transmitters that continuously signal their locations to tracking antennas on the ground; these are called beacons. Other spacecraft, such as Gemini, include transponders in their payloads. A transponder is a beacon that sends out a signal when it is triggered by a radio or radar signal from Earth.

1 *Satellites are best seen visually just after sunset and just before sunrise. Satellites can also be artificially "illuminated" by radars, lasers, and radio transmitters.*



Beacons and transponders eventually fail and their signals fade away. The spacecraft then becomes "dark" or "inactive" and must be illuminated by the Sun or a powerful Earth-based radio transmitter if it is to be tracked.

Consider the different kinds of spacecraft and how their various flight regimes affect the way we track them. The flights of sounding rockets are short in terms of time and distance. They can be tracked easily by radars and telescopes located right at the launch site.

Satellites present a more difficult problem. As their launch rockets rise from the pad, gain altitude, and arch over toward the southeast out over the Atlantic (assuming a Cape Kennedy launch) they are followed by launch site radars and optical instruments. Jettisoning lower stages and ascending rapidly, the rocket is passed from tracking station to tracking station along the chain of islands and ships stretching to Ascension Island in the South Atlantic. As the spacecraft approaches Africa it should be in orbit. If the African tracking stations know where to look they can pick up (acquire) the satellite, track it, and pass it on to the next station. The point here is that satellite tracking requires stations around the world—in other words, a network of stations rather than a few instruments at the launch site.

Tracking lunar, deep space, and interplanetary probes is still more difficult. Not only do we need a worldwide network to watch them, but we must maintain contact with them when they are hundreds of thousands, even hundreds of millions of miles away. Such distances are far beyond the capabilities of the radars and optical tracking equipment so useful for following satellites. A special radio tracking scheme is needed.

Each type of spacecraft thus has its own set of requirements:

Sounding rockets—Launch site radars and optical tracking equipment.

Satellites—Worldwide networks of radio, radar, and optical tracking stations.

Space probes—Worldwide networks of long distance radio tracking stations.

The subject of spacecraft tracking is really twofold: (1) what are the technical methods for finding and pinpointing spacecraft; and (2) how can these techniques be organized into worldwide networks that can keep track of the hundreds of machines we have put into orbit.

Ranges And Networks

To keep tabs on its many spacecraft, NASA operates three global networks and sponsors the operation of a fourth:

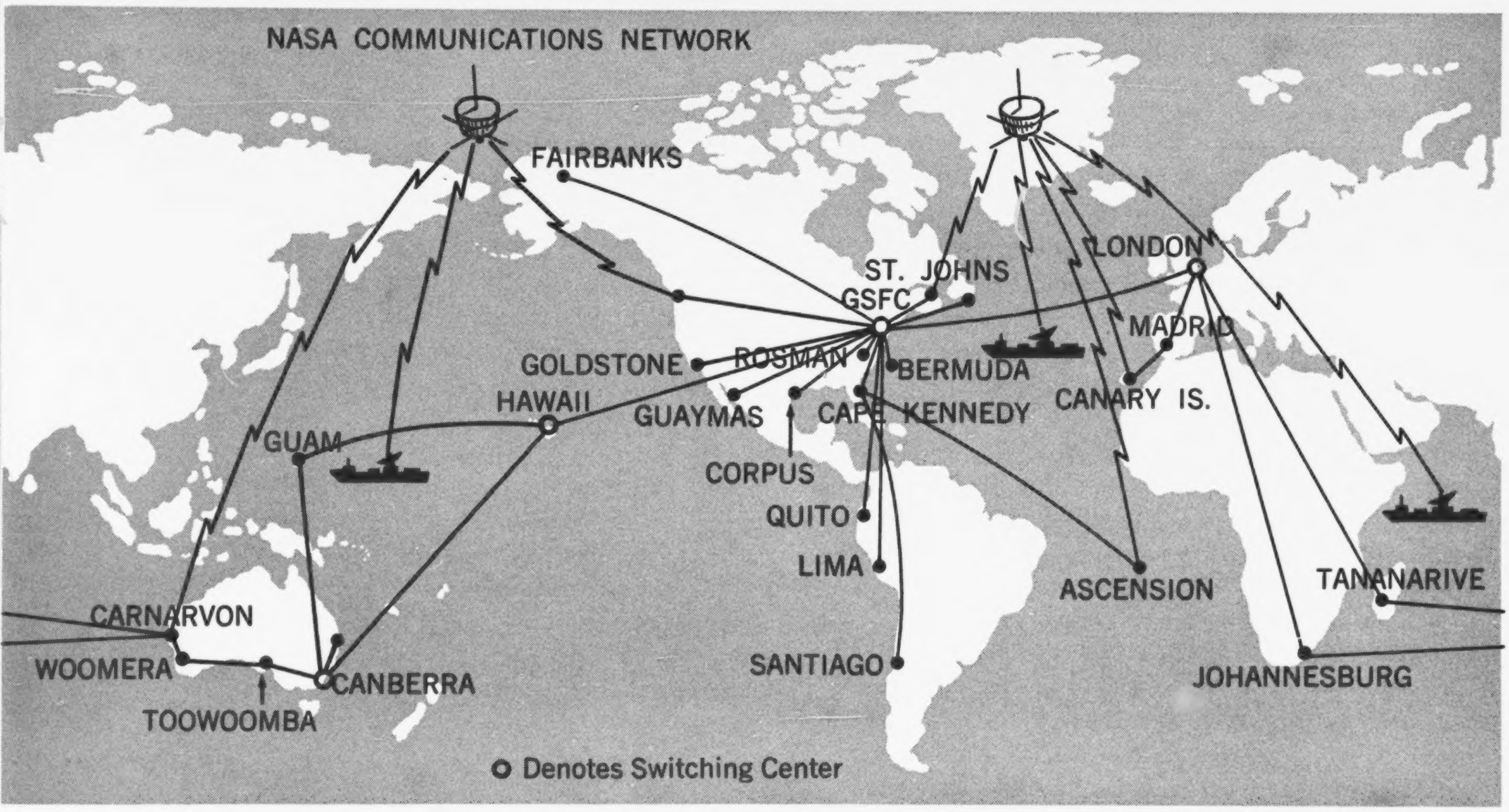
STADAN	Space Tracking and Data Acquisition Network	For tracking unmanned scientific and applications satellites
SAO	Smithsonian Astrophysical Observatory optical network	For precision tracking of satellites
MSFN	Manned Space Flight Network	For tracking manned satellites and lunar spacecraft
DSN	Deep Space Network	For tracking lunar, planetary, and deep space probes

Each of NASA's networks has a different mission that cannot be carried out well by any of the others. As the evolution of each network is described, it will be seen that the tracking techniques are fundamentally different for each. There is, however, considerable interchange of tracking data and continual mutual support among NASA's networks. This is also true for the worldwide networks maintained by the U.S. Air Force and Navy for tracking their military satellites.

A random sprinkling of tracking stations around the world does not make a network. The stations must be located where they will do the most good for the least cost. To illustrate, there are no tracking stations in Antarctica because it would be very expensive to maintain a station in that climate. NASA tracks its polar satellites from a station outside Fairbanks, Alaska. Most tracking stations, however, are concentrated within a wide equatorial belt 40° north and 40° south of the equator. The great bulk of U.S. spacecraft pass over this belt.

Tracking networks need good ties with the rest of the world, especially with the network control center, where

2 Map of major NASCOM communications lines. NASCOM provides worldwide real time communications between NASA tracking stations.


NASA COMMUNICATIONS NETWORK
FAIRBANKS
ST. JOHNS
GSFC
LONDON
MADRID
GOLDSTONE
ROSMAN
BERMUDA
HAWAII
GUAYMAS
CAPE KENNEDY
CANARY IS.
GUAM
CORPUS
QUITO
LIMA
ASCENSION
TANANARIVE
CARNARVON
WOOMERA
TOOWOOMBA
CANBERRA
SANTIAGO
JOHANNESBURG
○ Denotes Switching Center

all tracking and telemetry data converge for analysis. Three strong factors bind network stations together: (1) a high-speed, high-capacity communication system; (2) an accurate timing system; and (3) an accurate, common geodetic framework. The need for the second and third are obvious; we must know precisely where the stations are located (the geodetic factor) and we must have confidence that their clocks are synchronized; otherwise, tracking measurements will be worthless.

NASA ties its four networks together with a common communication system called NASCOM. Using submarine cables, land lines, microwave links, and communication satellites, NASCOM operates in what astronautical engineers call real time. This means that commands, data, and voice messages are transmitted anywhere on Earth in only a fraction of a second. NASCOM employs hundreds of thousands of miles of communication circuits plus a main switching center at Goddard Space Flight Center, Greenbelt, Maryland, and subsidiary switching centers overseas. NASCOM is not only vital to the tracking and control of spacecraft but it is a valuable national resource as well.

Before describing NASA's big networks, tracking ranges should be discussed. A range is a localized version of a network. For sounding rockets, a single tracking station with a variety of instruments suffices.

For missile and high altitude aircraft tests, a chain of interconnected stations is employed. A range is linear and of limited length, not two-dimensional and worldwide like a network. Nevertheless, its stations must be tied together in the same ways network stations are unified, and the tracking equipment is similar.

The biggest U.S. ranges extend outward from Cape Kennedy, Florida, and Vandenberg Air Force Base, California. The Eastern Test Range (ETR) begins at Cape Kennedy and runs southeastward along a string of islands and ships for some 5000 miles. NASA operates facilities at some points along the ETR. On the West Coast, Vandenberg is the hub of four separate ranges collectively called the Western Test Range (WTR). NASA launches most of its polar satellites from here. In between Cape Kennedy and Vandenberg, the U.S. operates ten smaller ranges.

NASA operates two of these smaller ranges: Wallops Island, on the Virginia coast; and the X-15 High Range, at Edwards Air Force Base, in the California desert.

From Wallops NASA launches many upper-atmosphere chemical-cloud experiments that are seen for hundreds of miles. A few small satellites, such as Explorer XVI, have been launched from Wallops on the Scout rocket. Several varieties of radars line the beach at Wallops, tracking sounding rockets, small satellites and pilotless aircraft launched from the several pads at Wallops. The Spandar radar with its 60-foot paraboloidal reflector is particularly impressive. It can track spacecraft 5000 miles away. A large number of tracking telescopes and cameras complement the radars. Wallops also employs an instrumented ship, the Range Recoverer, as a downrange station.

STADAN

STADAN, NASA's Space Tracking and Data Acquisition Network, grew around the basic core of eleven Minitrack tracking stations set up by the U.S. Naval Research Laboratory for the Vanguard Program in 1956 and 1957. In the early days of the space effort, Minitrack was the bulwark of U.S. tracking operations. Its radio interferometers still track most of NASA's scientific satellites and any other spacecraft carrying 136 MHz* radio beacons.

3 *The Spandar radar antenna at Wallops Island. Other radars are shown in the background.*

The Minitrack Electronic Fence

Suppose you shoot a volleyball-sized sphere into orbit from Cape Kennedy; you then turn and face west and wonder when, where, and even *if* that tiny sphere is going to come in over the horizon at 16,000 miles per hour. It would be almost impossible to find it with narrow-angle tracking telescopes and thin, pencil-like radar beams. To be certain of finding their satellites Vanguard engineers built an electronic fence that the spacecraft would have to cross if they were in orbit. This fence formed the basis of the Minitrack Network. The name Minitrack comes from minimum weight tracking; the weight being that of the tiny radio transmitter aboard the miniaturized Vanguard satellite. Having a voice of its own, a Vanguard satellite announced itself to the north-south fence of radio listening posts along the 75th meridian from Washington, D. C., deep into South America. The fan-shaped receiving patterns of the north-south Minitrack stations overlapped so that passing satellites had to cross the fence.

** 1 MHz = 1 megahertz = 1 megacycle per second = 1,000,000 cycles per second.*

4

4 *Optical tracker at Wallops Station.*

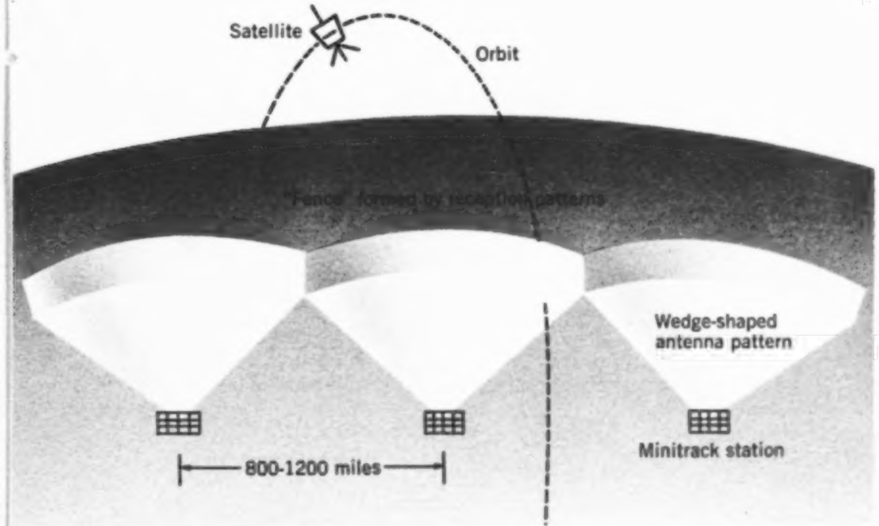
5 *The early Minitrack stations along the 75th meridian formed an electronic "fence" that satellites had to cross.*

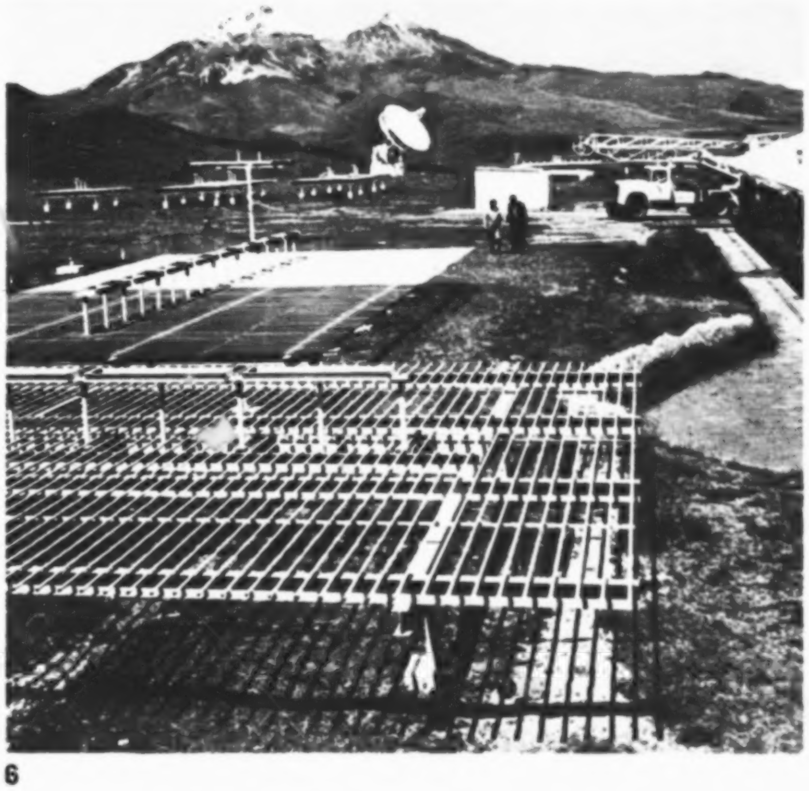
6 *The Minitrack array at Quito.*

By crossing the Minitrack fence, a satellite merely announced that it was there—hardly the accurate tracking data the Vanguard engineers wanted. A scheme was found that utilized the radio waves from the satellite transmitter to fix the satellite position. The basic idea came from the science of optics. It was called interferometry; and it had been employed for decades to measure angles and distances with fantastic accuracy. In radio interferometry, the idea is scaled up from the wavelengths of light (5×10^{-5} cm) to radio wavelengths (about 300 cm for Minitrack). Consequently the instrument itself grows from tabletop size to football-field size.

A radio interferometer determines the direction of the signal source very accurately. If we set up a line of equally spaced radio receiving antennas, say, north-south along our football field, they will not in general receive the crest of each satellite-sent radio wave at the same instant. If the satellite flies north of the station, the northernmost antenna will be the first to pick up the crest of the wavefront; the southernmost will be the last. Only if the satellite is plying a perfect east-west course bisecting the station's antenna array will all antennas receive the wavefront at the same instant.

5


Satellite
Orbit
"Fence" formed by reception patterns
Wedge-shaped antenna pattern
Minitrack station
800-1200 miles

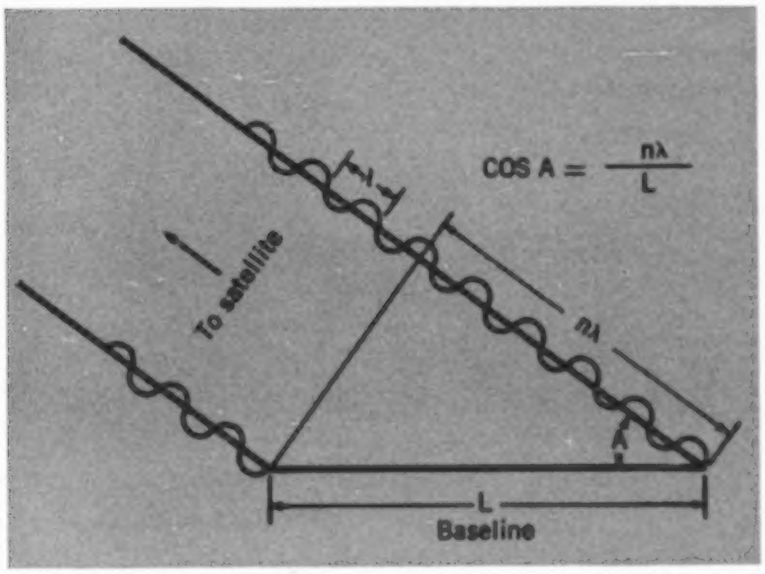


6

A Minitrack interferometer measures the angle the satellite-transmitted wavefront makes with the north-south line of antennas. It does this by counting the number of wavefronts that pass before adjacent antennas receive the same wavefront. (See diagram.) Angular precision comes from installing many separate receiver antennas in a line at each station. By using long antenna baselines at each station and then combining tracking data from several stations, the Minitrack system can measure the angular position of a satellite to within 20 minutes of arc.

A north-south line of receiving antennas in itself is insufficient because only one satellite angle can be computed. To measure the second angle, Minitrack stations also have an east-west line of antennas. The complete Minitrack antenna array forms a cross at each station. Along the 75th meridian, the north-south antenna patterns of the stations combined to create the original Minitrack fence.

Unlike radar and other tracking schemes, Minitrack radio interferometry does not provide target range and velocity; only target direction. Angular data alone, however, are sufficient to establish a satellite's orbit.



7 *An interferometer measures the angle of a transmitting satellite by the phase difference between the radio waves received at different receiving antennas in a linear ground array.*

The Minitrack network went into operation in October 1957, just after Sputnik 1 was launched. It proved highly successful in tracking the early U.S. Vanguard and Explorer satellites. In October 1958, newly created NASA absorbed Project Vanguard and, along with it, the operating responsibility for the Minitrack network. As NASA laid out its plans for space exploration, it became apparent that some Earth satellites, and lunar probes especially, could not be tracked accurately by radio interferometers.

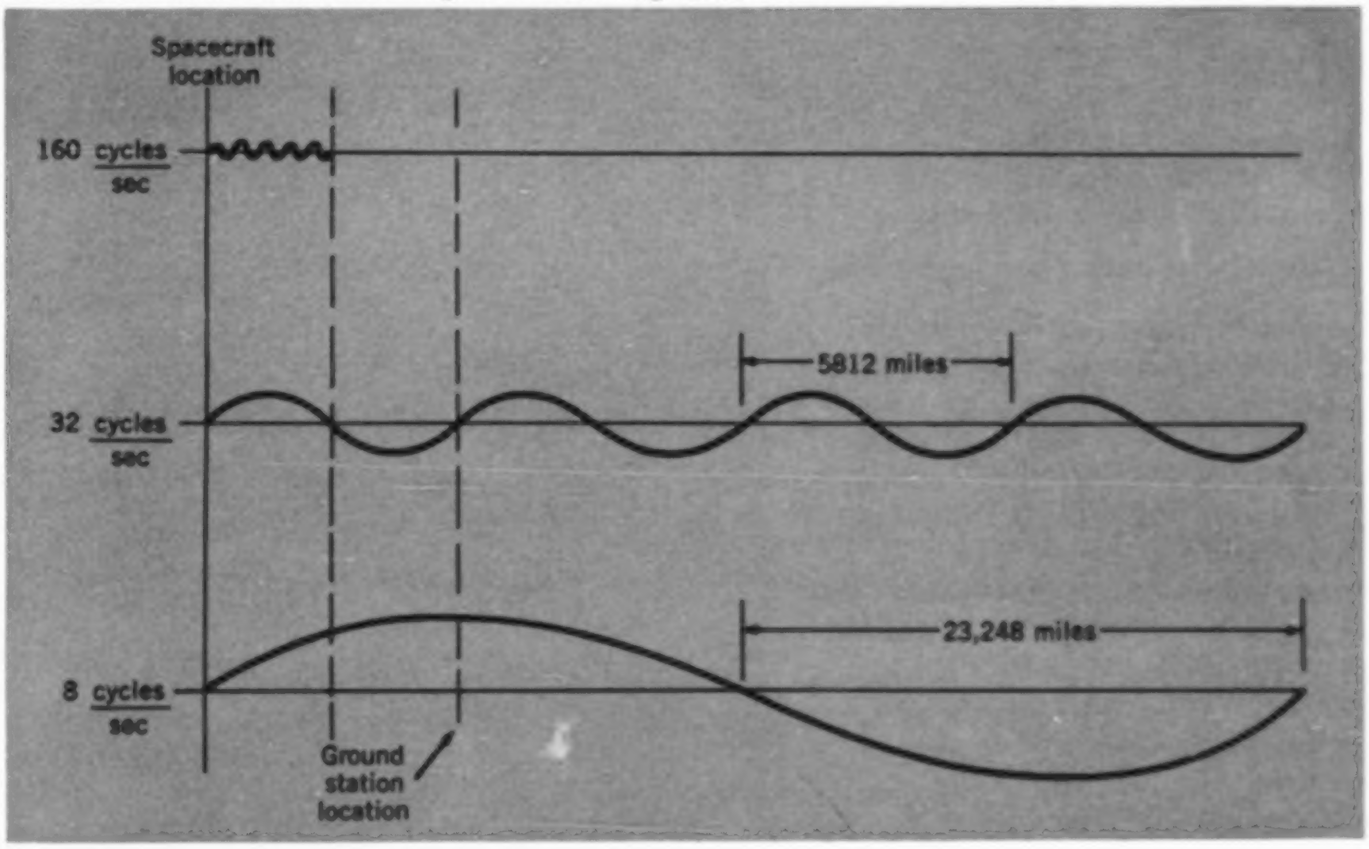
Sidetone Tracking

Suppose that NASA has just launched a spacecraft toward the Moon. Minitrack stations can measure its angular bearing as it heads toward the Moon; but is that sufficient? As the probe leaves the Earth behind, its angular bearing becomes less and less important because its motion is almost entirely directly away from Earth. The probe may travel 10,000 miles with hardly a change in its angular bearing. The same sort of difficulty arises with Earth satellites in highly elliptical orbits. Here, angular bearing remains almost unchanged when the satellite is traveling slowest near apogee. Minitrack angle tracking had to be supplemented with range and range rate (velocity) tracking.

NASA's Goddard Space Flight Center developed a tracking system based on the "range and range rate" technique, without the use of radar. The satellite or probe carries a special transponder that is triggered by a signal from an Earth-based tracking station. In response, the transponder emits a radio signal (called the carrier) that is modulated by eight mathematically related signals called sidetones. The transponder carrier signal is at 1705 MHz, but it is varied* at 8, 32, 160, 800, 4000, 20,000, 100,000 and 500,000 cycles per second. Except for the 8 at the beginning of the series, the sidetones form a geometric progression. Each of the sidetones may be thought of as a ruler. The 100,000-cycle/sec ruler is 1.86 miles long—the distance from crest to crest of the radio waves. The 20,000-cycle/sec sidetone ruler is five times longer, or about 9.3 miles. At 32-cycles/sec, the measuring stick is about 5812 miles long.

Actually the carrier's phase is varied, but this subject is beyond the scope of this booklet.

8 *The Goddard range and range rate system may be conceived in terms of radio wavelengths as measuring sticks.*



When the satellite transponder replies to the signal from Earth, it constructs (by radio) eight separate, parallel lines of rulers between itself and the Earth station. If the spacecraft is 5812 miles away, there will be exactly one 32-cycle/sec between spacecraft and Earth. How does the tracking station know that it is not really looking at the end of the second 32-cycle/sec ruler and that the spacecraft is really 11,624 miles away? This ambiguity, as tracking engineers call it, can be resolved by looking at the much longer 8-cycle/sec sidetone. The relationship between the two sidetones will be quite different if there are two 32-cycle/sec rulers rather than one. In a similar fashion, the station's electronic circuitry can distinguish between other arrangements of rulers.

The smallest sidetone ruler (the 500,000-cycle/sec one) is only about a third of a mile long. By comparing the wave shapes of the high frequency sidetones, a NASA tracking station can compute spacecraft range to within 45 feet, even if the spacecraft is as far away as the Moon. Range rate (spacecraft velocity toward or away from the station) can be found by measuring the Doppler effect; that is, the amount the transponder wavelengths are compressed or stretched by the motion of the spacecraft.* Range rate can be measured to within 4 inches per second for a spacecraft at lunar distances.

The introduction of range and range rate equipment at certain Minitrack stations was one of the changes that caused the metamorphosis of Minitrack into STADAN. Two other major changes were:

1. A general rearrangement and consolidation of stations. Rearrangement occurred when NASA no longer needed all the stations in the electronic fence along the 75th meridian because better tracking at the launch ranges provided good orbital data a few minutes after liftoff. Instead, NASA needed high latitude stations to track polar satellites, such as the Polar Orbiting Geophysical Observatories and the Nimbus weather satellites.
2. The addition of large 40-foot and 85-foot-diameter steerable paraboloidal dishes at several stations to permit faster collection of data from

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The common analogy refers to the rise and fall of the pitch of a train whistle as it approaches and recedes from the listener.

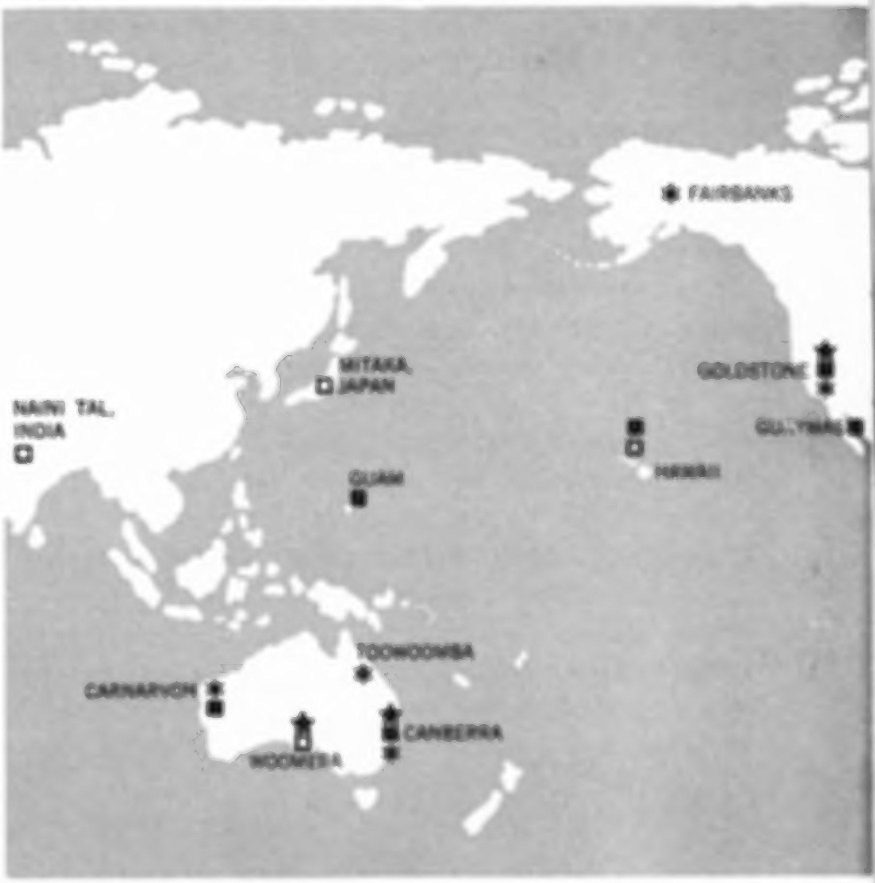
big NASA satellites, such as the Orbiting Geophysical Observatories and Nimbus satellites. These big dishes are usually *not* used for satellite tracking.

STADAN today, when compared with its progenitor Minitrack, consists of fewer, better equipped, and more widely distributed stations. Actually, the most important function of STADAN is now data acquisition rather than tracking. The hub of STADAN is at Goddard Space Flight Center, where all NASCOM communication lines converge. Scientific and applications satellites are controlled from Goddard by commands dispatched from Goddard via NASCOM to the STADAN station working the satellite of interest. The STADAN station relays the command to the satellite on the uplink portion of the radio link and receives data on the downlink portion. In essence, STADAN plus satellite form a huge, electrically connected machine run by mission controllers at Goddard.

The Smithsonian Optical Network

The Smithsonian Optical Network evolved concurrently with the Minitrack network in 1956 and 1957. In those days, no one knew for sure that radio interferometry would work well in tracking satellites. For this reason, the United States developed two separate systems based on different principles.

The Sun is obviously the best satellite illuminator of all. Unfortunately, most satellites are so small that they can be seen only with good telescopes. And just where does one point the telescope? The sky is a big place to search at random for a pinpoint of light moving slowly across the celestial sphere. Furthermore, satellites are not illuminated by the Sun at all when they are in the Earth's shadow; and in the daytime the poor contrast between satellite and bright sky makes seeing poor. The best time to see a satellite by sunlight is just before dawn and just after sunset, when the satellite is lit but the Earth below is not.

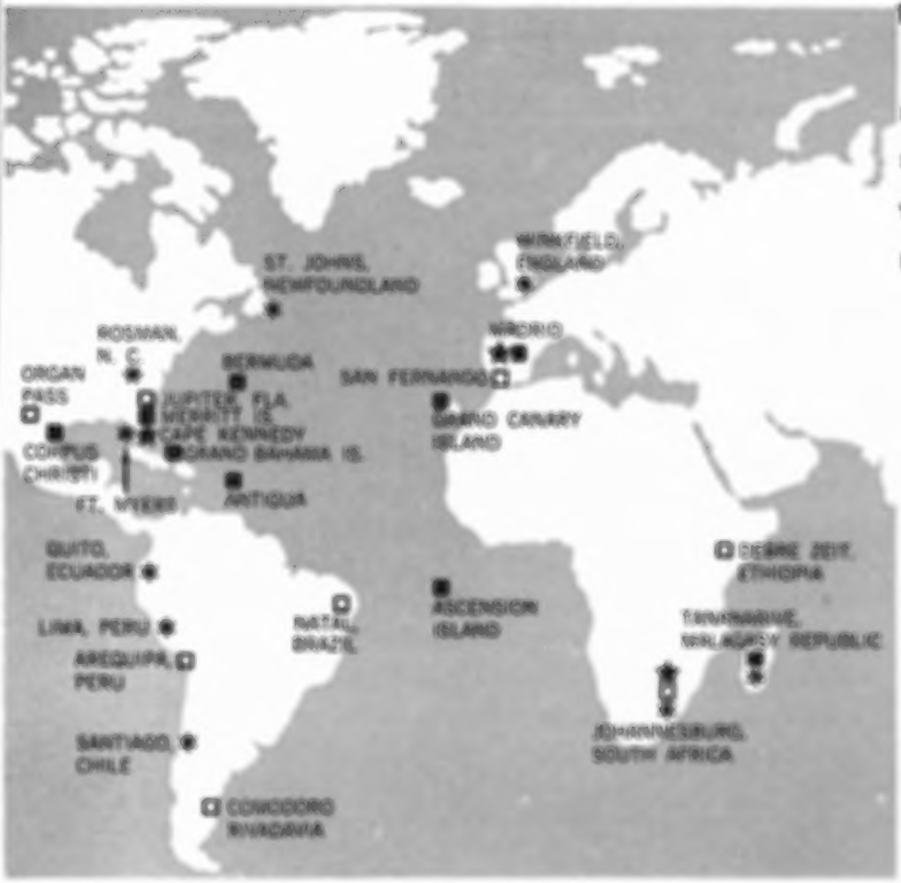


9 One of the two 85-foot telemetry receiving antennas at the Rosman, N.C., STADAN station.

The Smithsonian Astrophysical Observatory (SAO), set up an effective plan for optically finding and then precisely tracking the country's first artificial satellites.

The optical location of a satellite is simple in principle: organize lots of people the world over to watch the dawn and twilight skies. This was the core of the SAO Moonwatch Project. Through the astronomical fraternity and the great enthusiam for space in 1957, the SAO was able to establish almost 200 teams of amateurs in this country and abroad. Moonwatch teams were armed with low power telescopes. Several team members would arrange their telescopes north-south along the local meridian, creating in effect an optical fence analogous to the Minitrack radio fence. With Moonwatch teams on the lookout all over the world, someone would see a new satellite eventually. When a team spotted a satellite-like object, it immediately telegraphed the object's time of passage over the local meridian to SAO Headquarters in Cambridge, Massachusetts. With enough telegrams in hand, the SAO computer could calculate a crude orbit.

But a crude orbit is of little value to scientists who want to analyze slight orbital changes (perturbations) caused by the Earth's bulge and the pressure of sunlight. in the SAO scheme, Moonwatch was only the satellite finder. For precision tracking of satellites once they were located approximately, the SAO built a special camera that photographed them against the background of the fixed stars. Since the positions of the brighter stars are known with great precision, the satellite's


ST. JOHNS, NEWFOUNDLAND
WINKFIELD, ENGLAND
MADRID
ROSMAN, N. C.
BERMUDA
SAN FERNANDO
ORGAN PASS
JUPITER, FLA.
MERRITT IS.
CAPE KENNEDY
GRAND BAHAMA IS.
GRAND CANARY ISLAND
CORPUS CHRISTI
FT. MYERS
ANTIGUA
QUITO, ECUADOR
DEBRE ZEIT, ETHIOPIA
ASCENSION ISLAND
NATAL, BRAZIL
LIMA, PERU
TANANARIVE, MALAGASY REPUBLIC
AREQUIPA, PERU
JOHANNESBURG, SOUTH AFRICA
SANTIAGO, CHILE
COMODORO RIVADAVIA

10 Locations of major NASA Tracking Facilities.

■ MANNED SPACE FLIGHT NETWORK

✱ SPACE TRACKING AND DATA ACQUISITION NETWORK

★ DEEP SPACE INSTRUMENTATION FACILITIES

▣ OPTICAL TRACKING NETWORK

11 The Baker-Nunn tracking camera.

image* on the photographic plate would also be known very accurately.

The special, wide aperture camera, known as the Baker-Nunn camera, was the most important piece of hardware in the SAO optical tracking program. With a 30° field of view it can photograph a satellite too faint to be seen with the naked eye. By careful measurement of the images on Baker-Nunn plates, the angular position of a satellite can be found to within two seconds of arc (compared with 20 minutes for Minitrack).

The SAO installed Baker-Nunns at 12 stations around the world, generally within a belt 30° above and below the equator. The primary task of the big cameras has been high precision optical tracking of satellites for geodetic and geophysical studies. Although the Baker-Nunns provide more accurate tracking data than the Minitrack interferometers, analysis of the plates is lengthy and laborious. Minitrack and the SAO optical network turned out to be complementary. The former is good for locating satellites and providing approximate orbits; the latter is more precise once the satellite's rough location is known.

The success of Minitrack in finding satellites led to the disbanding of the Moonwatch teams in the early 1960s. The SAO network, which is run by SAO for NASA, has changed little since 1958. Its 12 cameras have materially advanced the science of geophysics with a minimum investment of money.

The Manned Space Flight Network (MSFN)

The purpose of NASA's Manned Space Flight Network is to track and communicate with manned spacecraft in Earth orbit or on a voyage to the Moon and back. Satellites are satellites; why not use STADAN for tracking manned satellites rather than build a whole new network? It is the payload—the astronaut—that makes the difference. We could allow an unmanned satellite to splash into the Atlantic and sink, but not an astronaut.

**a satellite's image is actually a short streak because a satellite moves across the sky much faster than the more distant fixed stars.*

Suppose a manned satellite is launched from Cape Kennedy out over the Atlantic. Within a few minutes it has pitched over and is headed downrange toward Africa with a speed approaching 15,000 miles per hour. But is it in a safe orbit? Its velocity could be just short of that needed for orbit so that it might impact on the African land mass. For the safety of the astronauts, we must know if the desired orbit has been attained *before* the point has been reached at which the spacecraft's path would cause it to impact in Africa. If a safe orbit has not been attained, the mission controller back at Houston can initiate an abort, causing the spacecraft to splash down in the Atlantic emergency recovery zone just before Africa. In other words we must know where a manned satellite is in real time; we cannot wait for Minitrack interferometer data from several stations to be analyzed. Radar provides the necessary split-second tracking data.

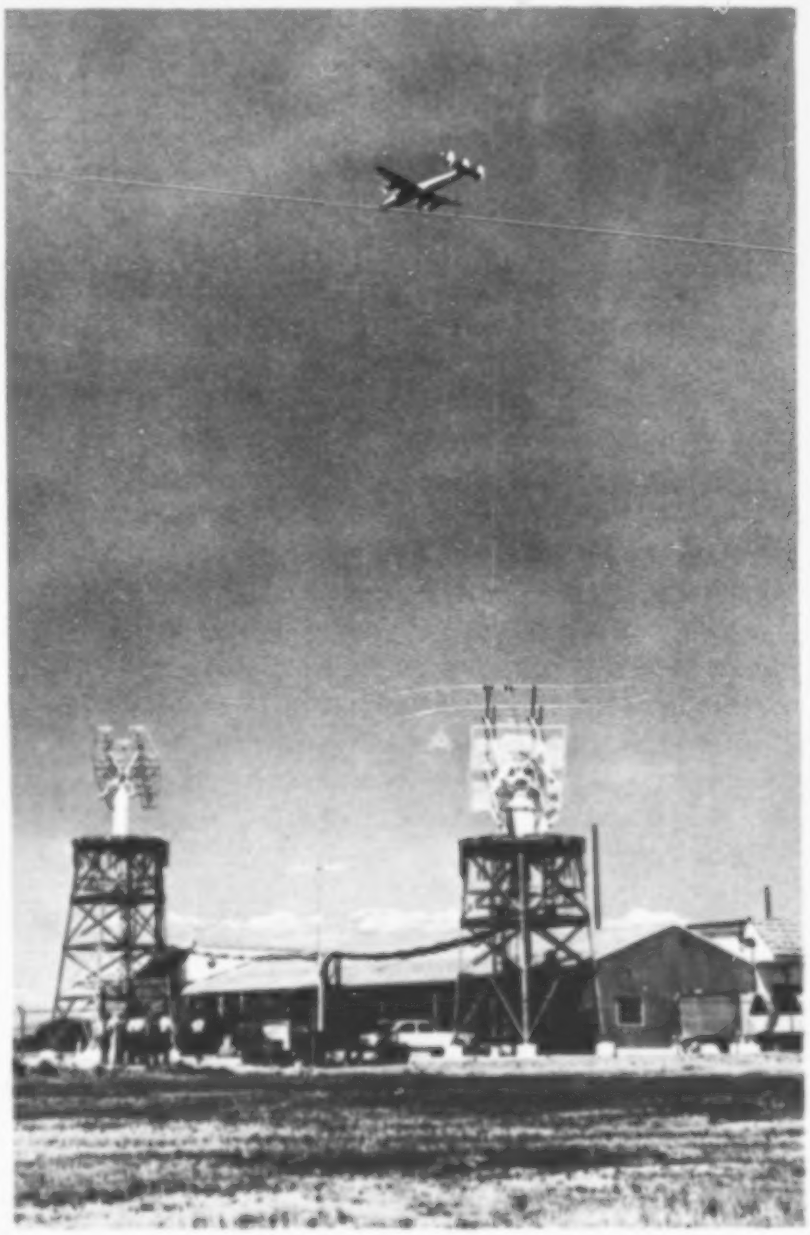
The tracking situation is much the same during reentry and recovery. The mission controller has to know exactly where the spacecraft is in order to fire the retrorockets at exactly the right time. If his timing is off, the spacecraft may land far outside the recovery area—perhaps on land. Rendezvous maneuvers in orbit also require real time tracking data. The MSFN, then, was built around the radar set.

How the MSFN Radars Work

On April 30, 1903, a German engineer named Christian Huelsmeyer received a patent for a "process for reporting distant metallic objects to an observer by means of electric waves." The essence of radar is found in Huelsmeyer's invention—the bouncing of radio waves off objects and listening for the echoes. A great deal more work was done by American and British engineers in the 1920s and 1930s before radar became a household word during World War II. Today, radar is sensitive enough to map the mountains on the Moon and detect a metal object the size of a dinner plate in a 500-mile orbit.

A radar transmitter is like a radio flashlight. Short radio waves—just a few centimeters from crest to crest—are squirted from a waveguide into a metallic

12 *The Guaymas, Mexico, station, showing tracking and data acquisition antennas.*



dish-shaped reflector. The reflector focuses them into a narrow, pencil-like beam similar to the flashlight's beam. A major difference is that radar's microwaves* are emitted in an intense pulse only a few millionths of a second long. During these scant microseconds, the radar may generate a million watts of power, in contrast to the flashlight's steady watt or two.

The pulse of radar waves moves out at the speed of light in search of the target. In a microsecond, it has already traveled 1000 feet; in 1¼ seconds it could reach the Moon. As the pulse travels, however, its intensity decreases according to the inverse square law—the pulse's power is cut to one fourth when the distance from the transmitter is doubled. When the pulse finally hits a target, only a tiny fraction of the radio energy in the pulse bounces back in the direction of the waiting radar antenna. The echo, moreover, also suffers at the hands of the inverse square law. The echo energy finally collected by the radar antenna has been weakened going out and coming back; its strength varies as the inverse fourth power of the target distance. The size, shape, and material of the target also affect echo strength. If the original transmitted pulse was at a power level of one million watts, the echo is often as weak as one micromicrowatt, representing an attenuation of 10^{-18}.

An MSFN radar measures the distance of a satellite by timing the echo. For every 10.7 microseconds delay, the target must be a mile away. A radar receiver thus must have a very fast electronic clock in addition to many stages of amplification.

Target detection and range measurement are only part of radar's stock in trade. From the antenna pointing angle, the radar operator gets target bearing, though not with Minitrack accuracy. Even more important, radar measures target range rate from the Doppler effect. By feeding radar-determined range and range rate into a computer that knows the laws of motion, we can determine the orbit of a satellite or the trajectory of a sounding rocket.

Because satellites are small and far away, it is customary to install a radar transponder on those that are to be tracked by radar. The radar pulse triggers the transponder, causing it to emit a pulse in response—a pulse that is much stronger than the normal echo. The radar antenna measures transponder responses rather than echoes. The strengths of these artificial echoes vary only as the inverse square of the distance, making the satellite easier to track.

Growth of the MSFN

Engineers at NASA's Langley Research Center, at Hampton, Virginia, began work on a worldwide radar, telemetry, and communications network for tracking manned satellites in 1958.

The network that finally evolved consisted of 18 stations stretching from Cape Kennedy southeastward; across Africa, the Indian Ocean, Australia; thence to Hawaii and the West Coast of the U.S.; across the continent to the Atlantic recovery zone. There were 16 land sites and two instrumented ships in a belt that lay beneath the three orbits originally planned for the most ambitious shots in the Mercury Program. All of the stations were linked by a terrestrial communication network to the Mission Control Center, at Cape Kennedy, and the computers at Goddard Space Flight Center, Greenbelt, Maryland. The Mercury Network became operational on July 1, 1961. It performed with high reliability during the entire Mercury Program.

When NASA's Gemini Program came along in 1963 with its two-man spacecraft and plans for rendezvous in space, the Mercury Network had to be modified in several ways. Because of the presence of two spacecraft in orbit during rendezvous maneuvers, the ground stations had to add extra antennas and more radio equipment to communicate with both sets of astronauts. The Mercury radars, however, were not changed because they could track both spacecraft by switching rapidly from one to the other. Some of the Gemini

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**Radar's microwaves are electromagnetic waves with wavelengths between roughly 3 mm and 30 cm. Visible light is also electromagnetic in nature, but the wavelengths are much shorter—400 to 700 millimicrons (4 to 7 x 10^{-7} meters).*

missions lasted as long as two weeks and the spacecraft traveled over a larger portion of the globe than any Mercury shot. Supplementary stations, including instrumented ships, were temporarily added to the Mercury Network for Gemini. Finally, there was a trend to consolidate tracking and communications into fewer, but better-instrumented sites. Overall, the changes for Gemini were minor. But it was during the Gemini Program (1963 to 1966) that the Mercury Network became the Manned Space Flight Network.

The Apollo Program, though, was a different matter; extensive changes in the network were required. When Apollo spacecraft leave the Earth far behind on their way to the Moon, they go beyond the range of conventional radars. The technical challenges and responses in planning the network are best summarized in a table:

New Apollo Requirement	MSFN Response
Range and range rate data essential for Moon trip	Adoption of Unified S-Band tracking approach (see USB, below)
Tracking and communication at lunar distances impossible for old MSFN equipment	Installation of three 85-foot-diameter paraboloidal antennas at DSN sites
Tracking and communication near Earth	Installation of 30-foot paraboloidal antennas at eleven MSFN sites
Expanded geographic coverage required to track and communicate with the spacecraft during and immediately following injection into the lunar flight path and for the reentry.	Addition of five ships, eight aircraft, a transportable station, many secondary sites, and communication satellites

The result of all these changes is that the old Mercury Network core is hardly discernible today. The most important new feature is the Unified S-Band approach.

Unified S-Band (USB)

USB stands for Unified S-Band. The adjective unified refers to the fact that, for the Apollo lunar mission, NASA has consolidated all of the tracking and communication functions (voice, telemetry, commands) into a single electronic framework, a single radio telecommunication link. Instead of independent, separate sets of equipment in the spacecraft and at each site for each of these functions, NASA has integrated everything into one set of hardware. The remainder of the system name comes from the adoption of frequencies in the so-called S-Band (1000 to 5000 MHz).

Intrinsic to USB is a tracking technique long employed by NASA's Deep Space Network (DSN) in tracking lunar, planetary, and deep space probes. The problems involved in tracking these distant spacecraft are essentially the same as those encountered with satellites in highly eccentric orbits—range and range rate data are essential where angular bearings change but little. In designing the USB, the approach to obtaining range and range rate was rather similar to that used in sidetone ranging. Instead of making phase measurements, however, the time of signal transit (round trip) is measured to obtain spacecraft range.

13

The Deep Space Network (DSN)

Neither the early MSFN radars nor the STADAN radio interferometers are of much help in tracking probes that leave the Earth far behind. A completely different system was developed by the Jet Propulsion Laboratory for tracking far-ranging probes through the solar system. Later, the MSFN adopted some of the JPL techniques in its system, and STADAN incorporated a range and range rate tracking system similar in some respects to the JPL approach.

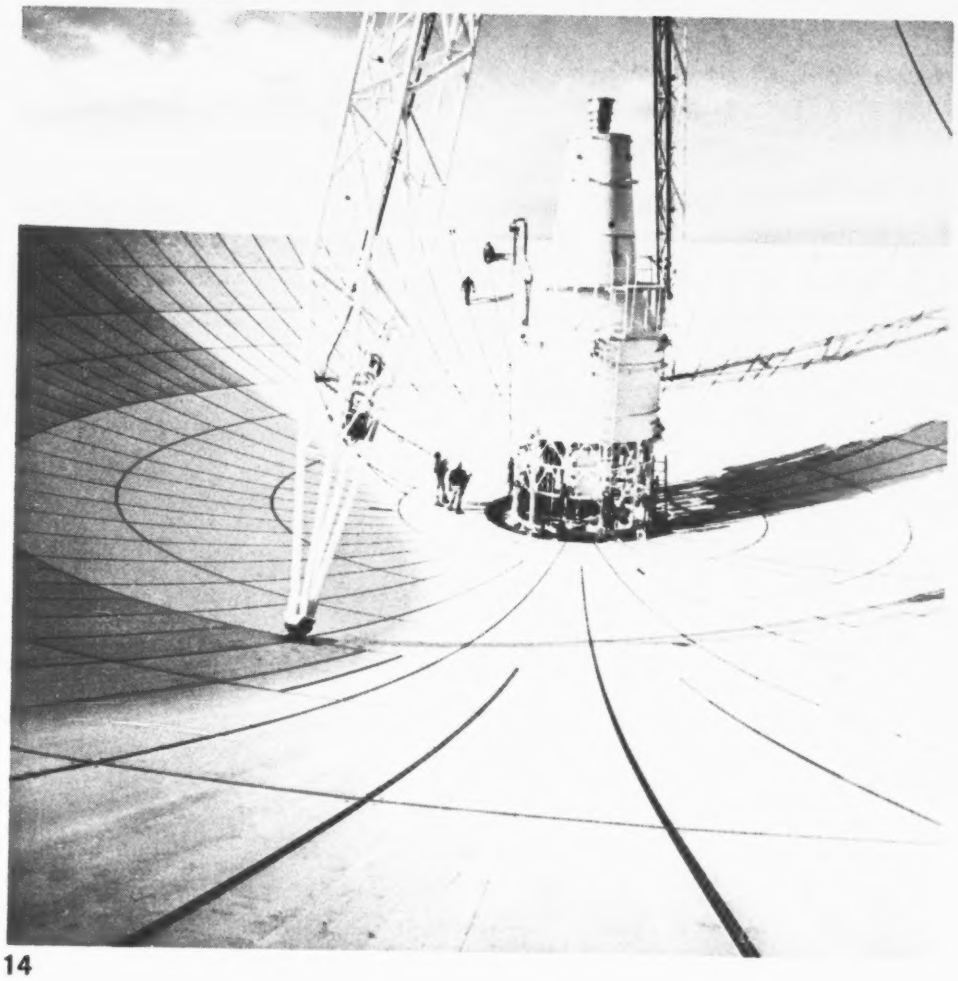
When the Jet Propulsion Laboratory programs were assimilated by NASA in December of 1958, JPL had already conceived the essentials of what was to become the Deep Space Network or DSN. The primary element in the tracking system was a large paraboloidal antenna with a narrow reception pattern. Angular bearings of distant spacecraft were found by centering them in this reception pattern and noting the antenna pointing angles. The spacecraft, of course, had to make itself visible through radio signals from its transponder. Range rate data were obtained from the Doppler effect. Finally, by triggering a transponder on the spacecraft and timing the round trip signal transmissions, range information resulted. Taken together, these data were sufficient for accurate trajectories.

NASA launched its first series of five Pioneer space probes in the general direction of the Moon between 1958 and 1960. They were the first U.S. spacecraft to be tracked by the embryonic DSN. During this period, the DSN did not have worldwide coverage. For example, for the flights of Pioneers III and IV, the DSN consisted of an 85-foot-diameter paraboloid at Goldstone, California, a 10-foot-diameter dish in Puerto Rico, and a still smaller antenna at the Florida launch site. The Jodrell Bank 250-foot radio astronomy antenna in England, and a 60-foot antenna at South Point, Hawaii (under Air Force operation) cooperated during the Pioneer Program by tracking the spacecraft when they moved out of the view of DSN stations.

How many stations are really needed to keep a spacecraft far out in space within view of at least one station? Two stations 180° apart are not sufficient because they would not provide sufficient overlapping of coverage of a deep space probe as the Earth rotates

13 *The Goldstone 210-foot paraboloid used for tracking probes far out in space.*

14 *Workmen standing in the reflector of the Goldstone 210-foot antenna.*



14

and the spacecraft passes from the view of one antenna into that of the other. Three stations spaced approximately equidistant around the Earth do the job well. The DSN was planned with this fact in mind.

By the time the first Ranger probes were launched toward the Moon in 1961, 85-foot dishes had been installed at Woomera, Australia, and Johannesburg, South Africa. With the Goldstone station, the trio was complete. During the early 1960s, the network was called the Deep Space Instrumentation Facility (DSIF). The DSIF tracked the first Venus probe, Mariner II, to a distance of 60 million miles in 1962.

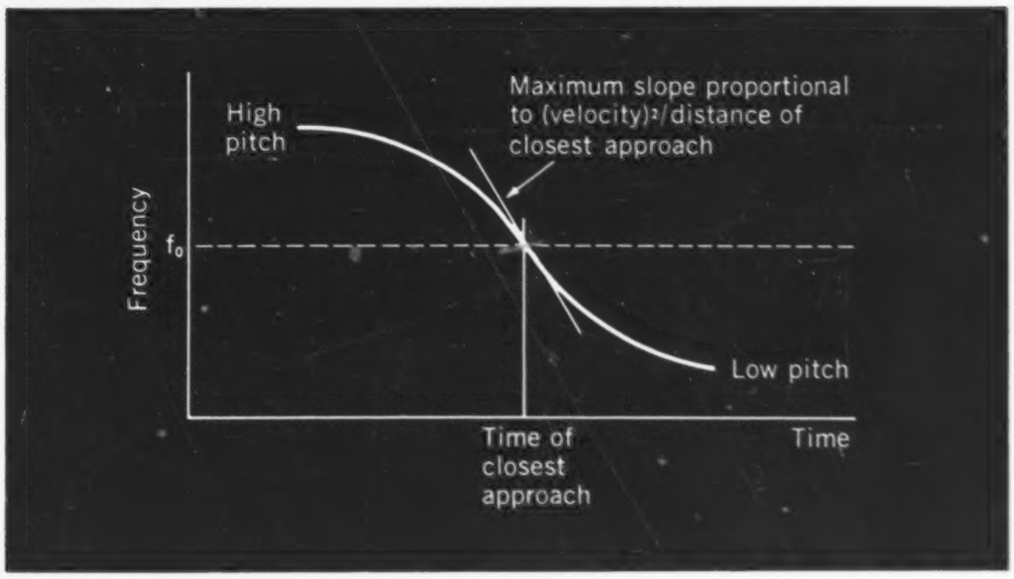
In 1965, the network (now called the DSN) guided Mariner IV to within 6200 miles of Mars. Mariner IV was some 135 million miles from Earth at the time of planetary encounter. After Mariner IV went into orbit around the Sun and became an artificial planet, the DSN tracked and communicated with the spacecraft at distances well over 200 million miles.

A major addition to the DSN in recent years has been a 210-foot paraboloidal antenna near the 85-foot dish at the Goldstone station. Antenna size is important in deep space work for two reasons: (1) the larger the antenna the more accurate the pointing data; and (2) the bigger the antenna aperture, the farther it can track a space probe, the more data it can receive from it per unit time, and the better it can control the space probe. With its 210-foot antenna, the DSN can work probes more than 200 million miles away and measure their ranges to within 45 feet and their range rates to within 1 millimeter per second.

In addition to the Goldstone 210-foot dish, NASA has added several more 85-foot paraboloids to the DSN to improve geographical coverage and support the Apollo Program. At Madrid, there are two DSN 85-footers and one belonging to the MSFN. Goldstone now has one MSFN plus three DSN 85-foot dishes. Finally, a DSN dish has been installed at Canberra alongside the 85-foot MSFN paraboloid. This redundancy increases astronaut safety during Apollo; if an MSFN paraboloid should go out of commission, a DSN dish will be ready to take over.

15 The Doppler record of a passing satellite permits computation of the orbit from the slope of the above curve.

16 Schematic of the laser tracking experiments performed with Explorer XXII.



15

Some Other Tracking Schemes

Harnessing the Doppler Effect

NASA uses the Doppler effect to compute range rate in radars, in sidetone approach, and in tracking deep space probes with the DSN. There is, however, a way to obtain all the data necessary for orbit computation by just listening (with radio ears, of course) to the beacon signal from a passing satellite.

A satellite approaching a ground station with a beacon emitting 136-MHz signals will appear to a ground station to be emitting signals a few kilohertz higher than it really is because of the Doppler effect. The signals will be correspondingly lower when the satellite recedes toward the opposite horizon. At one point in its transit across the sky, the satellite will appear to be emitting exactly the frequency it actually does emit; that is, the Doppler effect disappears. This occurs when the satellite is at the point of closest approach and is moving neither toward nor away from the ground station. In the train analogy, this is the instant when the train engine passes the observer.

If the apparent satellite signal is carefully plotted against time, a smooth curve connects the high-pitch and low-pitch plateaus. The shape of this curve is full of information that can be extracted by a mathematician. The speed of the satellite and the distance of closest approach can be obtained. In fact, enough information can be garnered from the Doppler record of one satellite pass to compute the complete orbit.

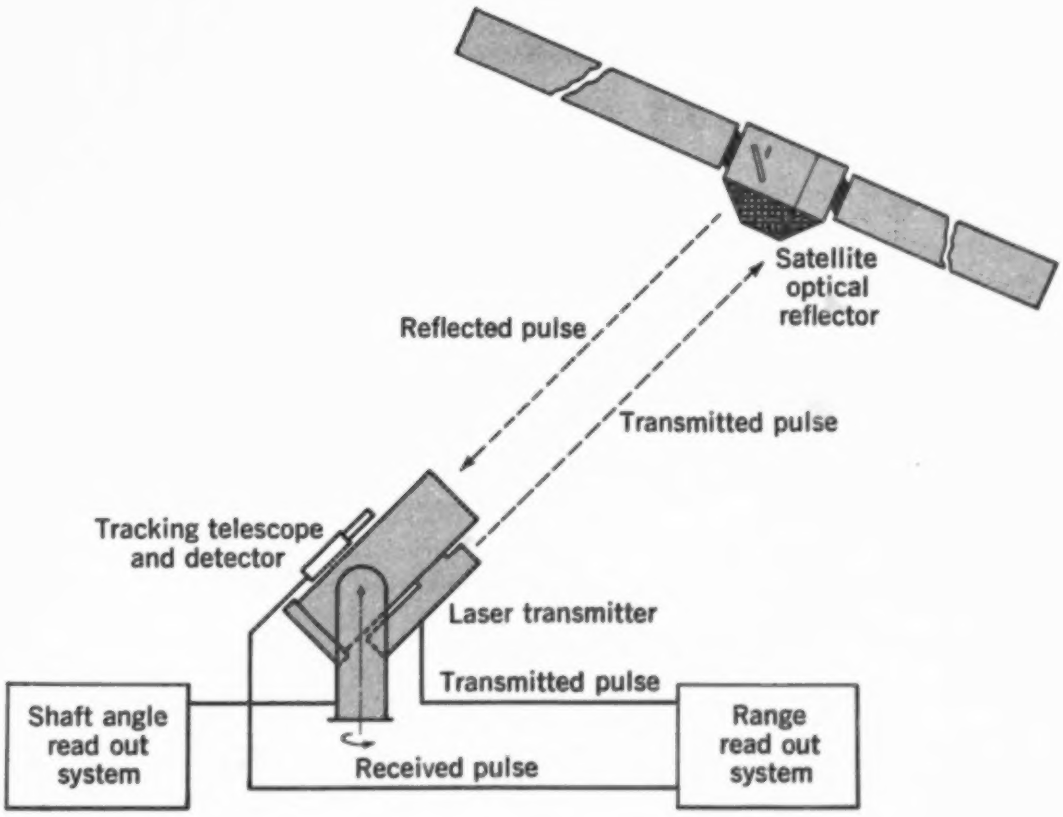
Doppler tracking is employed by the U.S. Navy in its navigation satellite program. Scientists also employ Doppler tracking to measure small changes in satellite orbits caused by variations in the upper atmosphere and the Earth's gravitational field. For example, variations in the density of the Earth below a satellite can cause its orbit to dip or rise a few hundred feet. Doppler tracking thus helps gain insight into the structure of the Earth's crust.

Laser Illumination of Satellites

In 1955 and 1956, when engineers were first studying the satellite tracking problem, powerful searchlights were considered for illuminating the satellite so it could be easily seen by ground stations. Searchlights were dropped in favor of radio interferometers; but the recent development of high power lasers reopened the question of artificial satellite illumination.

Lasers generate highly concentrated pulses of light energy—so powerful that they may be used to weld metals. Laser light is also nearly monochromatic; that is, almost all of one wavelength, like a radar pulse. Laser tracking, then, would be similar to radar tracking: a laser would be aimed at a satellite and the reflected light would be detected and analyzed like radar's radio echo.

Laser tracking has proven successful in a limited way


Satellite
optical
reflector
Reflected pulse
Transmitted pulse
Tracking telescope
and detector
Laser transmitter
Transmitted pulse
Shaft angle
read out
system
Range
read out
system
Received pulse

16

with several satellites, especially Explorers XXII and XXVII. Both of these satellites were outfitted with arrays of quartz corner reflectors—little quartz cubes cut in such a way as to reflect laser light straight back at the laser ground station with high efficiency. In practice, the laser beam is so narrow and pencil-like that the location of the satellite has to be known accurately before a direct hit can be made. This has limited the use of lasers in tracking to special experiments in geodesy, in which scientists attempt to locate points on the Earth more accurately with respect to one another.

Traffic Jam In the Sky

The big NASA tracking networks are supported by military and foreign tracking networks. With dozens of radars, cameras, and interferometers scanning the heavens the world over, satellites do not get lost any more, as Explorer X did for a while in 1961. In ten years the tracking problem has changed from trying to find a lone satellite in an empty sky to trying to keep track of over a thousand pieces of hardware in orbit around the Earth, around the Moon, and cruising far out in deep space around the Sun. Instead of the Moonwatch teams and a few lonely, isolated Minitrack stations, we have now "wired the world," as one NASA tracking expert has put it. NASA can communicate with any of its active satellites and space probes at the flick of a switch—even if the spacecraft is on the Moon, flying by Mars, or taking pictures of the weather around Australia.

RECAPITULATION OF TRACKING TECHNIQUES

How We "See" Spacecraft	Tracking Technique	Examples of Use
Solar illumination	Optical tracking	Moonwatch, Baker-Nunn cameras, theodolites
Artificial illumination	Radars, lasers	Sounding rocket and launch ranges, the MSFN
Through beacons or transponders on spacecraft	Radio interferometers	STADAN (Minitrack) and various launch range tracking systems
	Sidetone tracking	USB, STADAN range and range rate system
	Doppler effect	Intrinsic in radars, sidetone, and DSN tracking
	Big radio dishes	DSN

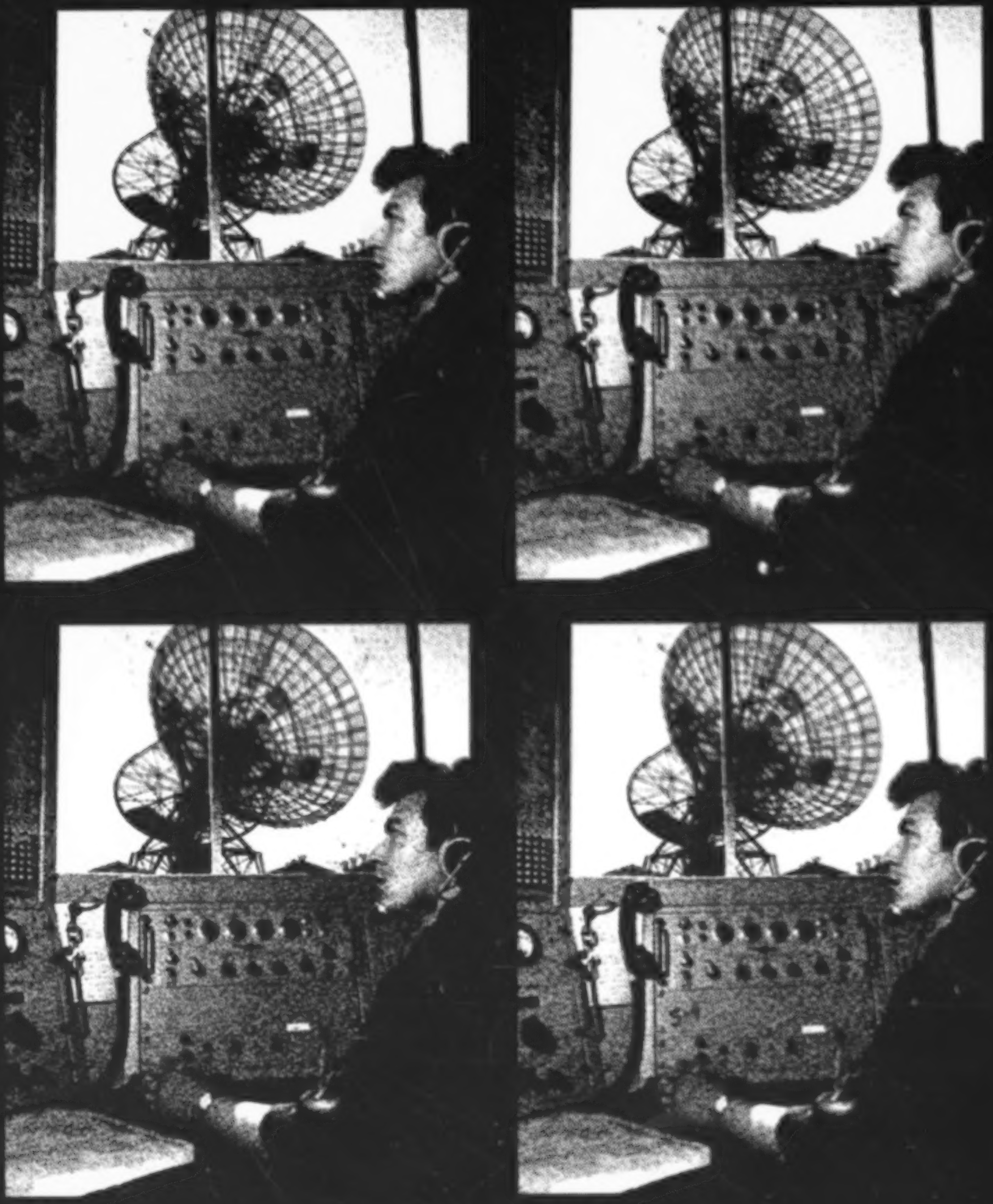
Additional Reading

For titles of books and teaching aids related to the subjects discussed in this booklet, see NASA's educational publication EP-48, Aerospace Bibliography, Fourth Edition.

NASA-Langley, 1968

America In Space | The First Decade

Linking Man and Spacecraft



National Aeronautics and Space Administration

America
In
Space:
The
First
Decade

This is one of a series of booklets published on the occasion of the 10th Anniversary of the National Aeronautics and Space Administration.
These publications are not intended to be comprehensive history, nor do they deal with all the facets of NASA's aeronautical and space activities. Rather they are overviews of some important activities, programs and events written for the layman in terms of the several science disciplines.

Each of these subjects is treated in more depth in other NASA publications and in scientific journals.

1 October 1968

Titles in this series include:

I Space Physics and Astronomy
II Exploring the Moon and Planets
III Putting Satellites to Work
IV NASA Spacecraft
V Spacecraft Tracking
VI Linking Man and Spacecraft
VII Man in Space

Others are in preparation. Topics include:

Propulsion
Spacecraft Power
Space Life Sciences
Aeronautics
Space Age By-products
Materials

LINKING MAN AND SPACECRAFT

by William R. Corliss

National Aeronautics and Space Administration, Washington, D.C. 20546

Introduction

For a decade, NASA has probed the cosmos with numerous manned and unmanned spacecraft, each having a specific purpose and each, most often, having its own unique characteristics. Yet, common to every undertaking, whether simple sounding rocket or complex manned Apollo, is the need to communicate between the ground and the spacecraft.

"Linking Man and Spacecraft" deals with the transfer of vital information between spacecraft and the Earth. Spacecraft communication is difficult to separate from spacecraft tracking in the sense that NASA's three worldwide ground-based networks perform both functions. Most NASA network stations possess systems that can simultaneously track and acquire spacecraft data. Despite this dual capability of NASA hardware, spacecraft tracking—a subject dealing with the precision location of spacecraft—has a different theoretical background. Because of this distinction,"Spacecraft Tracking" is the title of another booklet in this series.

Gerald M. Truszynski
Associate Administrator for
Tracking and Data Acquisition

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Linking Man and Spacecraft

Conversations With a Machine

A man who lifts his telephone receiver and dials a number commands a vast, electrically connected machine with hundreds of millions of input-output stations all over the world. NASA has constructed a similar man-machine system to control and converse with its spacecraft. NASA's machine is connected by hundreds of thousands of miles of submarine cables, microwave relays, and radio links. In the case of the planetary probe, Mariner IV, the man-machine system stretched some 200 million miles out into space.

The basic commodity of both the telephone system and the spacecraft communication system is information. On the downlink from the spacecraft come (1) scientific data from spacecraft instruments; (2) housekeeping data from thermometers and other instruments that gauge the health of the spacecraft; (3) tracking signals that help ground stations pinpoint the location of the spacecraft; and (4) the voices of the astronauts if the spacecraft happens to be manned. On the uplink travel commands to spacecraft equipment and the other half of the astronaut-ground controller conversation.

The complete space data system consists of much more than the radio link connecting Earth and spacecraft. Let us define the complete system by beginning with the data sources on the spacecraft and following the data through spacecraft circuits, to the Earth, through terrestrial data handling equipment, and finally to the ultimate user of the data.

The most prolific spacecraft data generators are the scientific instruments, such as Geiger counters and magnetometers. Television cameras on weather satellites are also prodigious gatherers of information. Collectively, satellite instruments gather over 200 million data points each day. These data converge on the spacecraft radio transmitters. Before they are dispatched to Earth, however, they are processed; that is, modified so that all are expressed in the same language or perhaps condensed through the removal of unimportant information. After processing, they move on to the transmitter, to the antenna, and to Earth. Radio antennas at terrestrial data acquisition stations follow the spacecraft, pick up radio signals, and convey them to receivers where they are amplified. If everything has functioned properly, the signals emerging at the receiver output terminals will be identical with those emanating from the spacecraft transmitter.

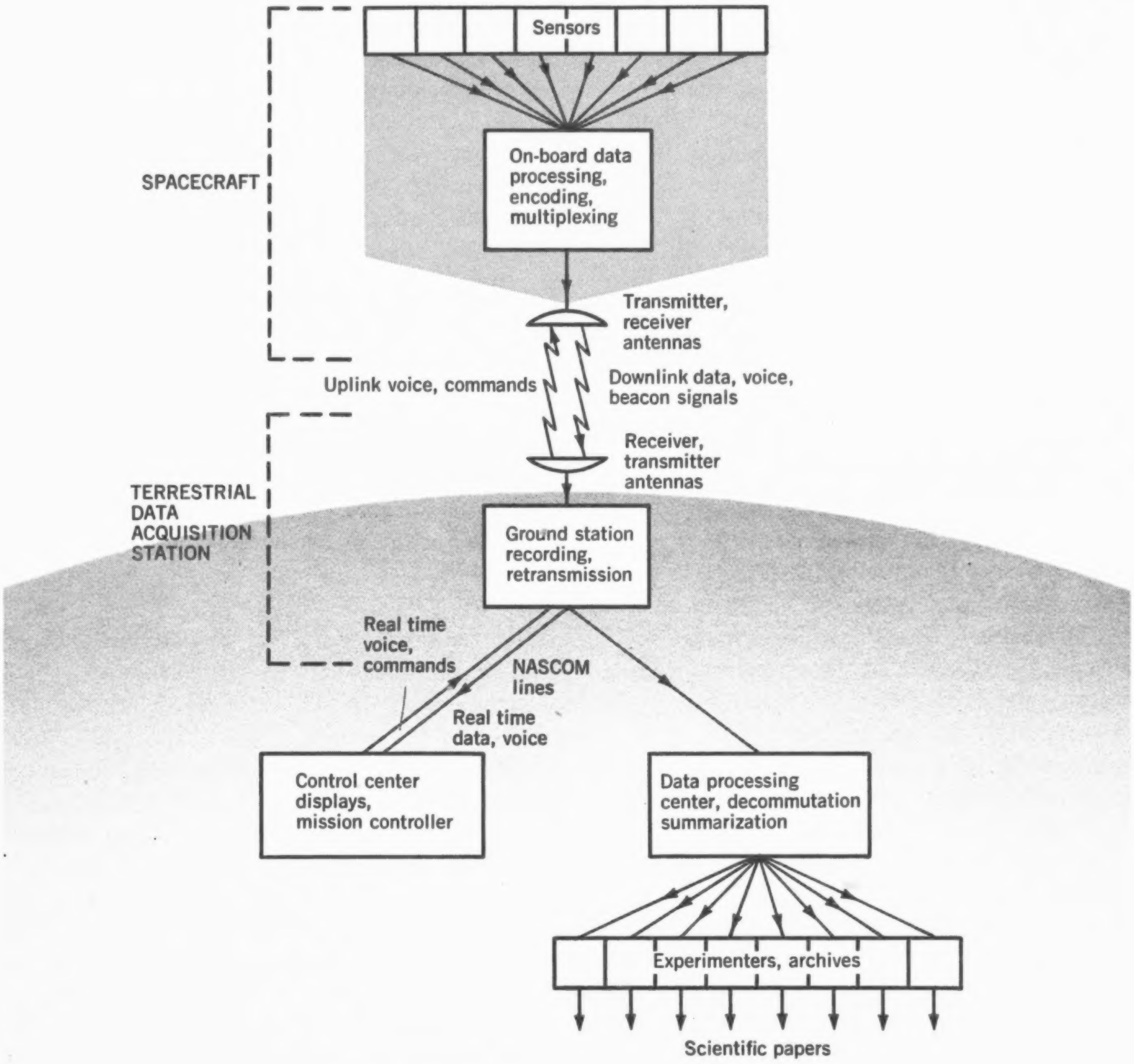
The trip is not over for the data. Important information is sent directly to the control center managing the spacecraft via NASA's worldwide terrestrial communication system NASCOM. Critical data are transmitted in real time, with total delays of less than one second. Most scientific data are recorded on magnetic tapes and shipped back to the control center by airmail.

At the control center, urgent data are usually displayed visually to the spacecraft controller, who then makes decisions and dispatches commands back to the spacecraft. The scientific data tapes are fed into computers that process the data and put them in the form most useful to the scientists. The computer may even draw graphs or summarize the data in other ways. This critical line of demarcation between man and machine is called the man-machine interface; it is here that machine is matched to man.

Once a scientist has digested the spacecraft data, he draws his conclusions, writes his reports, and publishes them for the world of science. The link between spacecraft sensor and the human data user is now complete.

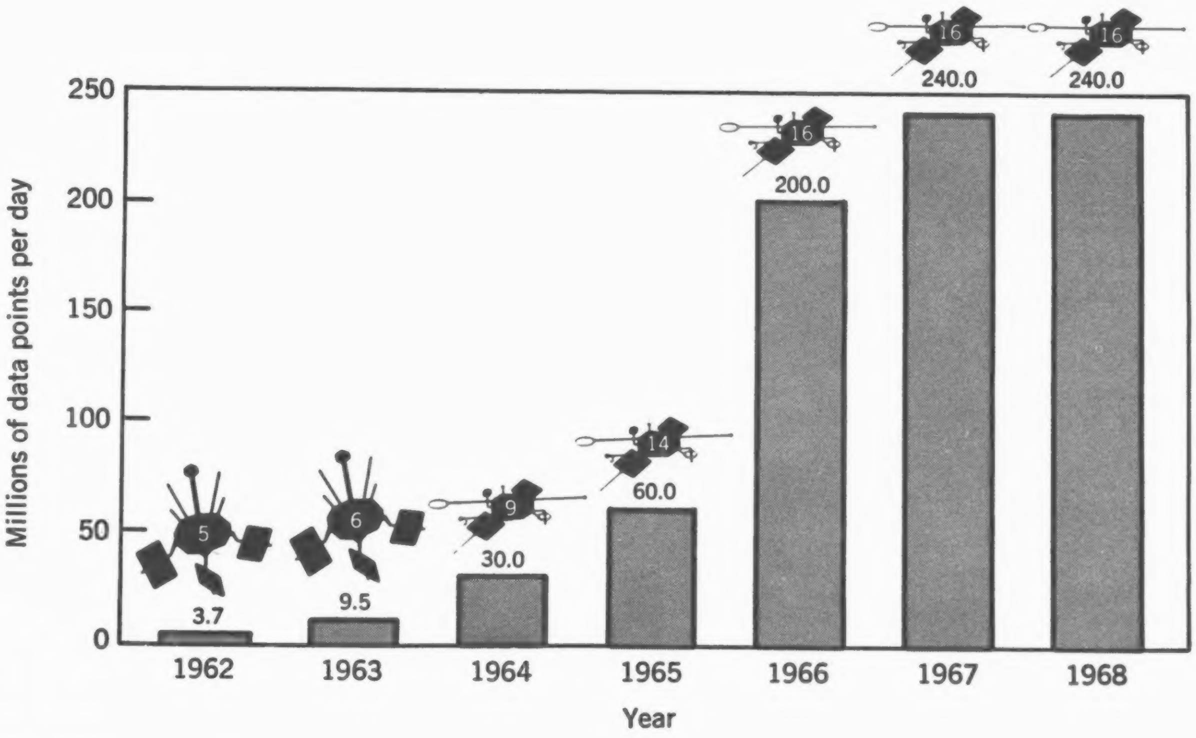
1 *Diagram showing how information flows between the spacecraft sensors and data users in a space data system.*

2 *Trend of data quantities produced by Earth satellites. The number inside each spacecraft indicates the number of launchings.*



Sensors
SPACECRAFT
On-board data processing, encoding, multiplexing
Transmitter, receiver antennas
Uplink voice, commands
Downlink data, voice, beacon signals
Receiver, transmitter antennas
TERRESTRIAL DATA ACQUISITION STATION
Ground station recording, retransmission
Real time voice, commands
NASCOM lines
Real time data, voice
Control center displays, mission controller
Data processing center, decommutation summarization
Experimenters, archives
Scientific papers

1



2

Some Space Communication Problems

The Question of Power

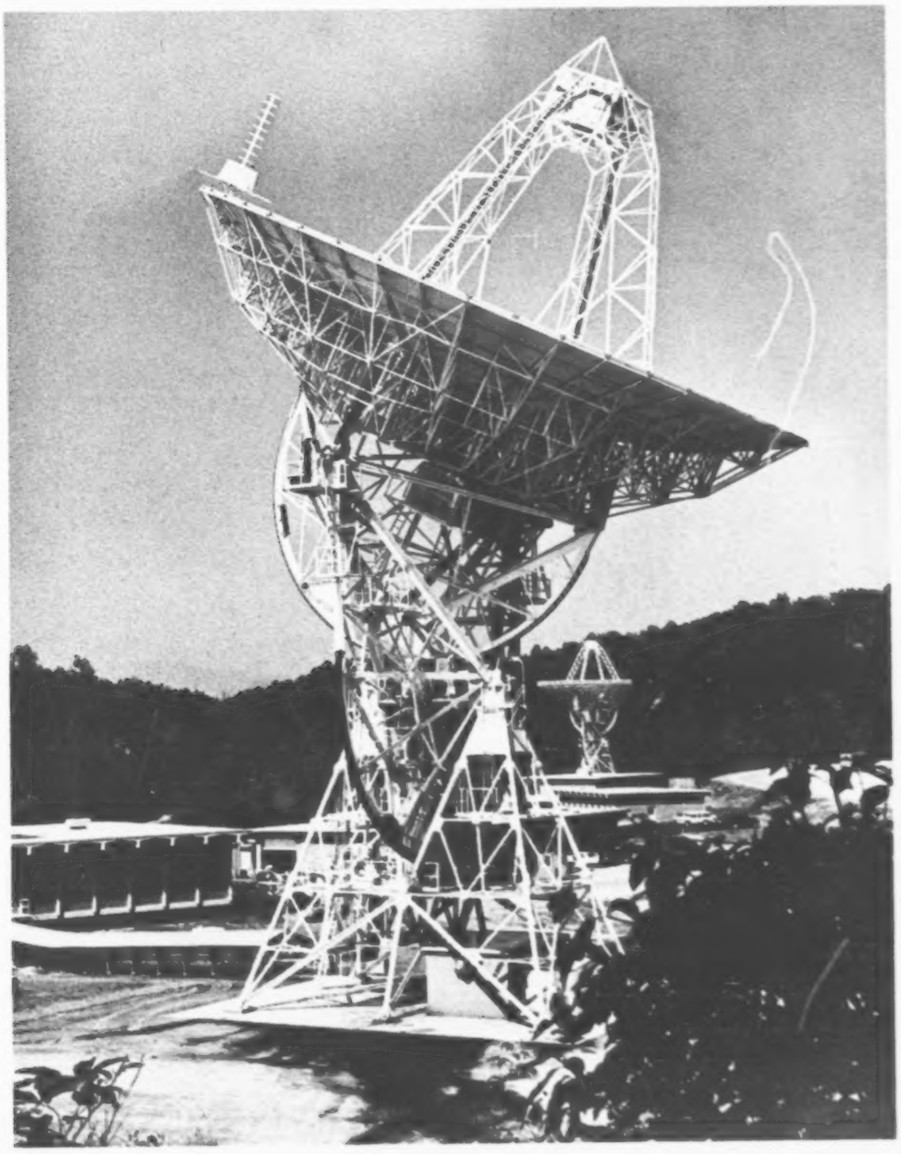
Conversing with satellites and space probes by radio is radically different from building a radio in the attic and talking to another amateur in Japan. The problem is sheer distance when communicating with a space probe at lunar or planetary distances. Earth satellites, however, are usually only a few hundred miles away when they pass over terrestrial data acquisition stations. In the case of satellites, the problem is transmitting the flood of data collected by the craft's instruments. Within limits, the problems of distance and data quantity can be solved by increasing the power level of the spacecraft transmitter. But power is not the only factor involved. To understand space communication, some technical terms must be defined:

Bandwidth: The faster one wishes to send information, the bigger the bandwidth has to be; that is, the larger the piece of the electromagnetic spectrum occupied by the radio signal. A radio channel bandwidth may be compared to a water pipe; if the pipe area is doubled, twice as much water (information) can be pumped. Unfortunately, doubling the bandwidth also doubles the power required.

Antenna Gain: The more sensitive the antennas on the spacecraft and at the data acquisition station, the easier it is to transmit information back and forth. Good antennas, at both locations, reduce the requirement for power aboard the spacecraft. Sensitive antennas are large and highly directional; they have to be pointed accurately. Antenna pointing imposes a burden on the spacecraft.

Noise: Radio noisemakers are everywhere: the Sun, the Milky Way, the Earth's atmosphere and warm surface, and man's multitude of machines. High transmitter power can drown out noise; a wise choice of transmitter frequency simplifies the problem.

Atmospheric Attenuation: Radio waves travel practically unhindered through outer space, but the Earth's atmosphere absorbs radio waves



3

4

uplink and downlink. Again, more transmitter power is a potential solution, though absorption is reduced greatly by selecting the proper frequency.

The radio engineer aims to insure that the signal power delivered to the radio receiver by the receiving antenna is greater than the noise power by a factor of ten or more. The receiver power is directly proportional to the transmitter power, the gain (amplification) of the transmitter antenna, and the gain of the receiving antenna. It is inversely proportional to the atmospheric attenuation and the square of the distance between the transmitter and receiver.

To illustrate the interplay between these factors, consider first a satellite transmitting three watts of signal power toward a data acquisition station on the Earth. The three watts is no more than the power consumed by a flashlight bulb, but it is sufficient for loud, clear satellite signals. Satellites are so close to the Earth that transmitter power can be used to increase bandwidth rather than overcome distance. In contrast to planetary probes, satellites transmit large quantities of data per unit time over relatively short distances.

NASA's Venus probe, Mariner II, also transmitted three watts of signal power in the direction of the Earth. But Mariner II's signal power was employed to conquer distance rather than increase bandwidth. Just after its encounter with Venus in 1962, Mariner II transmitted data across 36 million miles to Earth—a distance 100,000 times that of most Earth satellites. However, the data flow rate from Mariner II was many thousands of times less than it is for most satellites.

Power also overcomes noise. The Mariner II probe was so far away from Earth that one wonders how

3 *The Rosman, N.C. STADAN station. The two 85-foot dishes are used for acquiring data from the larger satellites.*

4 *For interplanetary communication, the paraboloid antenna on Mariner II had to be kept pointed at the Earth.*

its weak transmissions were ever heard above all the noise generated in space and on the Earth.

Space probes like Mariner II cannot spare the power necessary to blast through noise; noise reduction is the better solution. Therefore NASA has placed its data acquisition stations in areas where man-made noise is weak. The Goldstone station in NASA's Deep Space Net, for example, is far out on the California desert, ringed by hills that cut off noise emanating from cities on the Pacific coast.

Noise created within the receiving equipment itself is reduced by cooling the most sensitive portions of the receiver to near absolute zero with liquid helium. The intense cold slows the motion of the noise-making electrons in the circuitry.

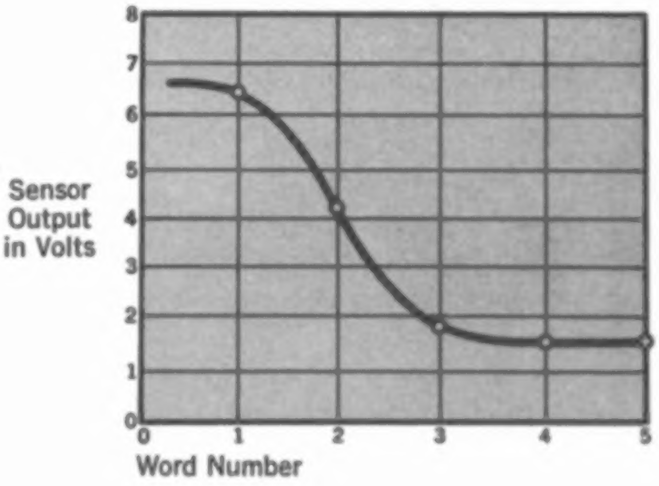
Since the signal power at the receiver terminals depends directly upon the gains of the transmitting and receiving antennas, NASA has emphasized the design and installation of large, sensitive antennas at its Earth-based data acquisition facilities and on the spacecraft proper. In particular, the Deep Space Net, which must maintain contact with probes across the solar system, searches the sky with paraboloidal dishes 85 and 210 feet in diameter. The gain of such an antenna is very high in the direction it points. If the probe is slightly off the antenna axis, however, its signals will go unnoticed. The probe itself obviously cannot carry an 85-foot paraboloid into space, but dishes several feet in diameter are common on probes. When spacecraft and terrestrial antennas are pointed right at each other, the product of their respective gains will be maximum and so will the signal power at the receiver. The terrestrial antenna can be pointed by man, but that of the probe must be pointed toward the Earth by the spacecraft which is free to turn in all directions.

The effectiveness of the space data system thus depends to some degree upon the ability of the spacecraft to locate Earth, lock onto it, and turn its antenna in the right direction. The space data system cannot be designed independently of the spacecraft and its capabilities. The astronautical engineers call this an *interface* between the space data system and the spacecraft attitude control subsystem.

Of Bits, Codes, and Languages

Information is the basic commodity of communication. A bit is the smallest amount of meaningful information that can be exchanged: that amount of information inherent in a yes or no; a 1 or a 0; an electrical pulse or its absence; or any other two-valued phenomenon. A bit is a digit in the binary system of numbers; the binary system is based on powers of two.* Any number may be represented by an equivalent binary number; decimal 11 for example is 1011, a four-bit binary word. If a satellite Geiger counter counts 11 Van Allen region electrons per second, it can so inform the experimenter on Earth by sending a train of pulses so: ⎍_⎍⎍ pulse—no pulse—pulse—pulse, to represent 1011. Continuously varying (analog) data can be approximated by a series of binary numbers as shown in the illustration. The spacecraft

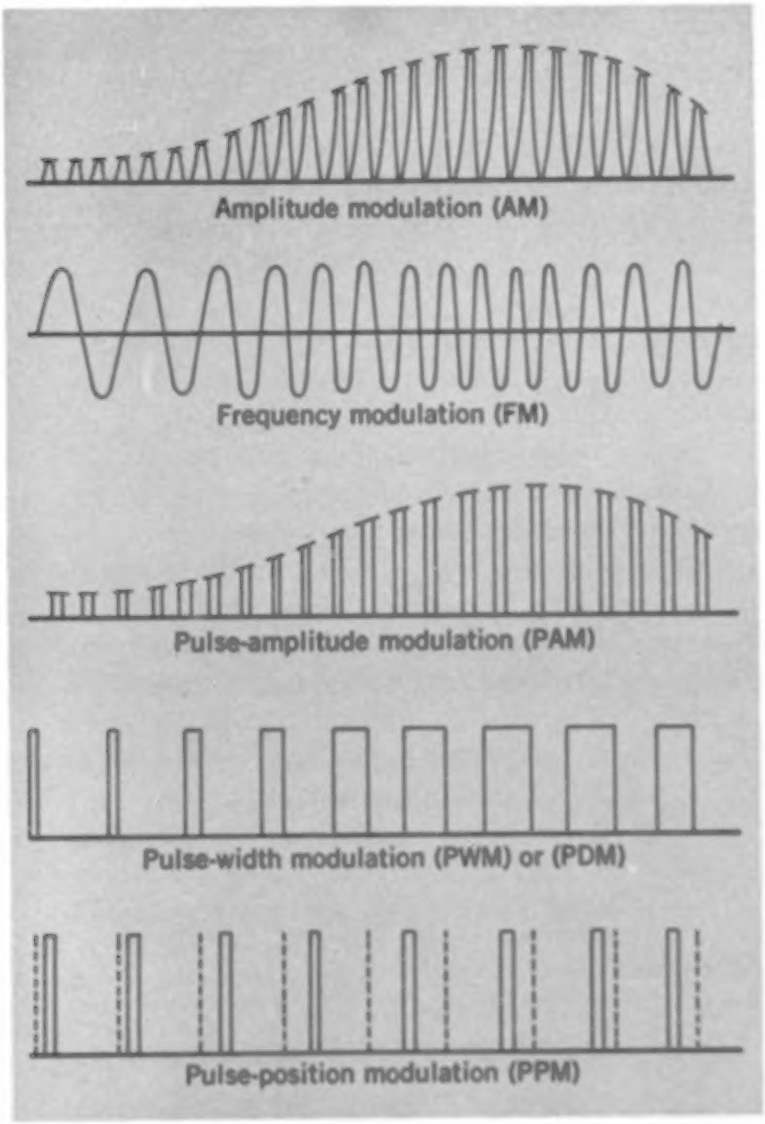
5 *An analog signal represented by 3-bit and 4-bit words. A 3-bit word permits a resolution of 1 volt; a 4-bit word allows a resolution of 0.5 volt.*



Data word number	Decimal sensor reading	3-bit words	4-bit words	4-bit pulse train
1	6.3	110	1101	⎍⎍_⎍
2	4.1	100	1000	⎍___
3	1.8	010	0100	_⎍__
4	1.6	010	0011	__⎍⎍
5	1.7	010	0011	__⎍⎍

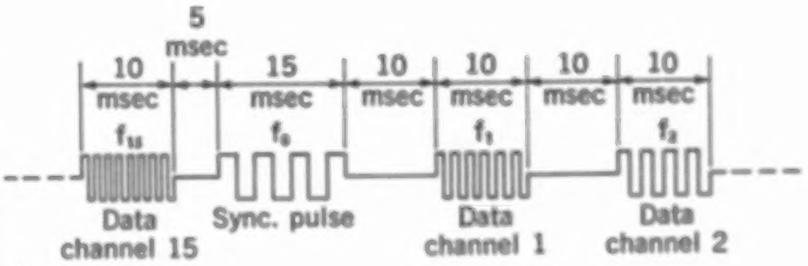
**Using three-bit "words," the binary-decimal equivalents are:*

000 = 0   011 = 3   110 = 6
001 = 1   100 = 4   111 = 7
010 = 2   101 = 5


Amplitude modulation (AM)
Frequency modulation (FM)
Pulse-amplitude modulation (PAM)
Pulse-width modulation (PWM) or (PDM)
Pulse-position modulation (PPM)

6

6 A comparison of several types of telemetry modulation.



7

7 A train of PFM signals. The frequency of the pulses in each channel carries the desired data. The channels are time-division multiplexed. The sync pulse synchronizes the communication circuits.

can also report its switch positions to the mission controller; pulse for ON, no-pulse for OFF. Spacecraft temperature readings are easily transmitted as binary words.

The trend in NASA today is to convert most spacecraft transmissions into strings of pulses and no-pulses on both downlink and uplink parts of the space data system. There are exceptions; astronaut voice transmissions are not converted into the binary language, though they could be in principle. The binary language is often called machine language because it is the language of computers and most data processing equipment.

While many NASA spacecraft discourse with ground stations in machine language, different dialects exist. The differences come about as a result of the various ways information can be added to the transmitter's carrier waves; that is, the constant-frequency electromagnetic waves it emits when no information is being transmitted. The easiest and most primitive way to add information to (modulate) a carrier is simply to turn it off and on in Morse code fashion. This is effective but crude. More sophisticated are the amplitude modulation (AM) and frequency modulation (FM) that we receive on ordinary radios. In AM, the information is superimposed by varying the amplitude of the carrier. A 440-cycle/sec note (A on the musical scale) would be represented by a carrier whose amplitude varied between a maximum and a minimum 440 times per second. In frequency modulation, the frequency of the carrier would be varied back and forth between a maximum and a minimum frequency 440 times per second.

The amplitudes, widths, and positions of pulses can carry information, too. For example, pulse-amplitude modulation (PAM) and pulse-width modulation (PWM) have occasionally been used on spacecraft. The object of any form of modulation is to find some property of the carrier and vary it in a way that conveys information to the recipient.

NASA has developed a special type of modulation for its smaller scientific satellites. It is called pulse-frequency modulation or PFM. A data acquisition station listening to PFM from a satellite hears short bursts of pulses. The first burst in a sequence of bursts might come from experiment #1 on the satellite; call this channel #1. The frequency of the pulses in that burst is a measure of the output of experiment #1. If experiment #1 consists of a magnetometer, 1000 pulses per second on channel #1 could correspond to 100 units of magnetic field strength. If 2000 pulses per second are detected, the experimenter knows that the magnetometer is reading 200 units of magnetic field strength, and so on.

The second burst of pulses transmitted by the satellite might represent the output of a voltmeter in the spacecraft power supply, classifying channel #2 as a housekeeping channel. Ten volts might be equivalent to 1000 pulses per second here. So it goes; until all scientific and housekeeping instruments are read as a sequence of pulse bursts. Within each burst of pulses, the frequency of the pulses reveals the instrument reading.

The reading of each spacecraft instrument in sequence one after the other is termed time division multiplexing or commutation. Multiplexing is a general term applied when several channels of information are transmitted on the same carrier. A similar technique is employed when several telephone conversations are sent over the same wire at the same time. In time division multiplexing, each experiment is connected to one terminal of a many-terminal switch (called a commutator). As the arm of the switch rotates, it makes brief connections with each of the spacecraft instruments, thus sampling each instrument once per revolution.

On its bigger satellite and planetary probes, NASA uses pulse code modulation (PCM). PCM is pure machine language; a series of pulses and no-pulses, which are equivalent to a series of 1s and 0s. A 0 might be electromagnetically expressed as the carrier frequency f_0, while a 1 could be frequency f_1. In PCM, some property of the carrier is switched between one value and another; this property may be frequency, amplitude, phase, pulse width, or anything else that the Earth-based receiver can recognize as two-valued.

PCM has several desirable features from NASA's standpoint:

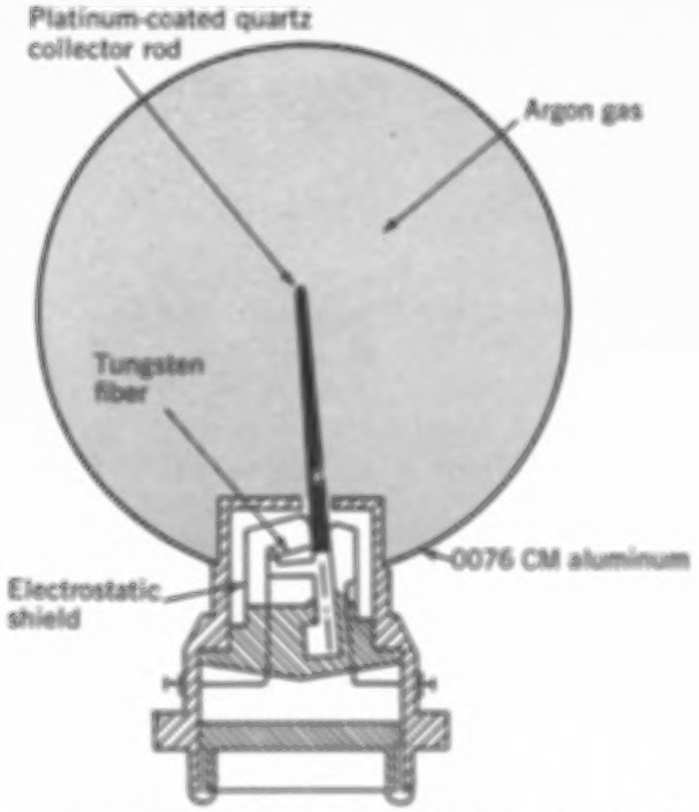
1. It is computer language. NASA's spacecraft can draw upon the immense technology developed by the computer industry.
2. Spacecraft can talk directly to NASA's complex of Earth-based computers, relieving man of the arduous task of translation.
3. All kinds of information can be encoded easily—readings from scientific instruments, commands to spacecraft equipment, etc.
4. If extremely high precision is required for some measurement, say, counting a million Geiger counter discharges, the size of the PCM word can be lengthened accordingly (to 20 bits for decimal 1,000,000). In contrast, it would be almost impossible to accurately distinguish a million different levels in AM and FM.

Spacecraft Sensors

If spacecraft are true extensions of man into space, should they not see, hear, and even extend his sense of touch to the planets? Spacecraft sensors see very well; they see much more of the electromagnetic spectrum than man's eyes. But there is very little to hear or smell in airless space. The sense of touch, however, would be useful when an Earth-based spacecraft controller wishes to manipulate rock and soil specimens on the Moon or some planet by remote control. NASA's Surveyor surface sampler simulated man's hand in a crude way and turned out to be a very effective manipulator of lunar soil. Surveyor's surface sampler had no sense of touch, but the spacecraft's legs were instrumented with strain gauges and other devices that gave engineers data on the properties of the lunar soil during touchdown.

Many spacecraft instruments are nonanthropomorphic; that is, they measure phenomena that man cannot perceive directly. Magnetometers, cosmic-ray detectors, and radio noise monitors are all examples of instruments that permit us to see facets of the universe that would be invisible otherwise.

NASA has flown many hundreds of instruments on its satellites, space probes, and sounding rockets. Just a list would take many pages. However, space instruments can be grouped



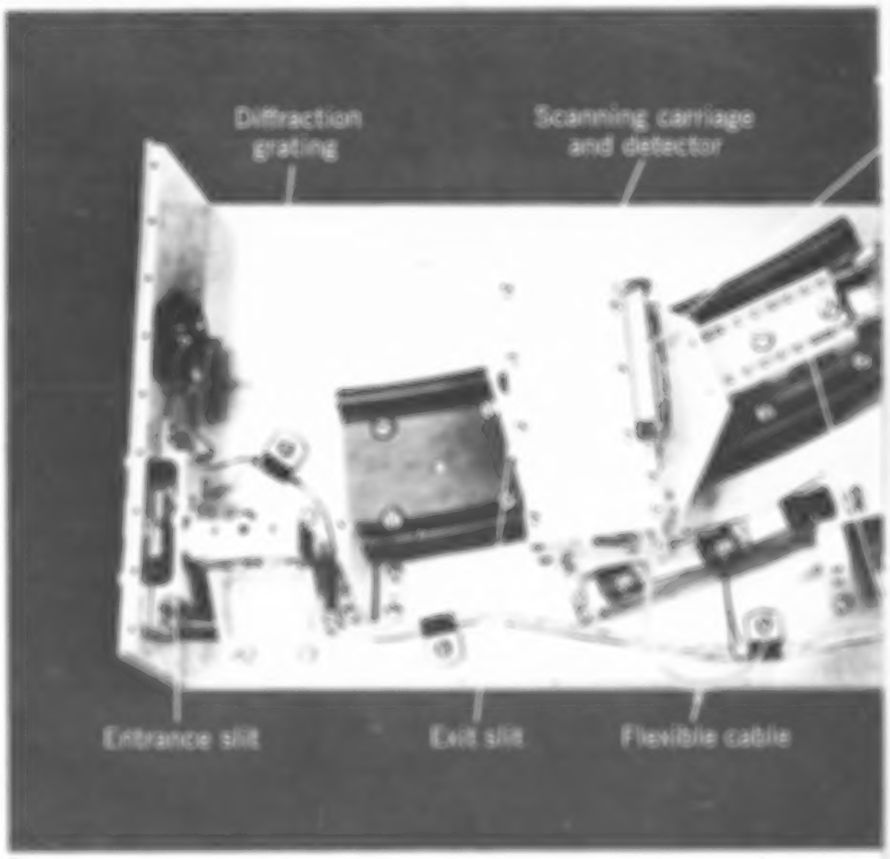
8 *The Neher ionization chamber produces a single pulse after a specific amount of radiation has passed through the sphere. Radiation causes the chamber to discharge, and the collector rod swings right closing an electrical contact. Most radiation-measuring instruments are counters of some sort.*

conveniently according to the phenomena they measure:

Class of Phenomena	**Typical Instruments**
Fields and particles	Geiger counters, magnetometers, plasma probes, ionization chambers
Planetary atmospheres	Pressure gauges, thermometers, air-glow photometers
Solar physics	X-ray photometers, ultraviolet spectrometers
Space astronomy	Telescopes (optical and radio wavelengths), gamma-ray detectors
Planetology	Cameras, surface samplers, soil composition experiments
Meteorology	Cameras, infrared radiometers
Bioscience	Astronaut electrocardiographs, life detectors

9 *This ultraviolet spectrometer was flown on OSO I. To scan the spectrum created by the grating, the detector was moved along the curved track by a motor. This spectrometer generated an analog signal. Compare this spectrometer with the much simpler Neher ionization chamber. Spectrometer is two feet long.*

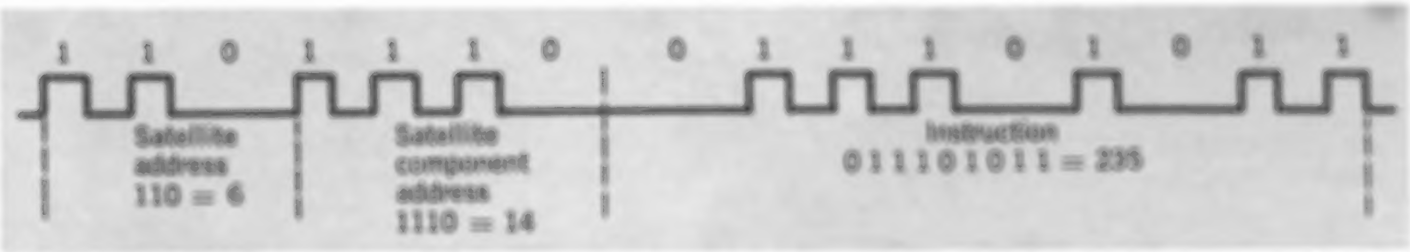
10 *A possible command to a satellite includes addresses plus a specific instruction. Shown in digital form is a command to satellite 6, component 14, to perform operation 235. Note the similarity to dialing a telephone number with area code, exchange, and number.*



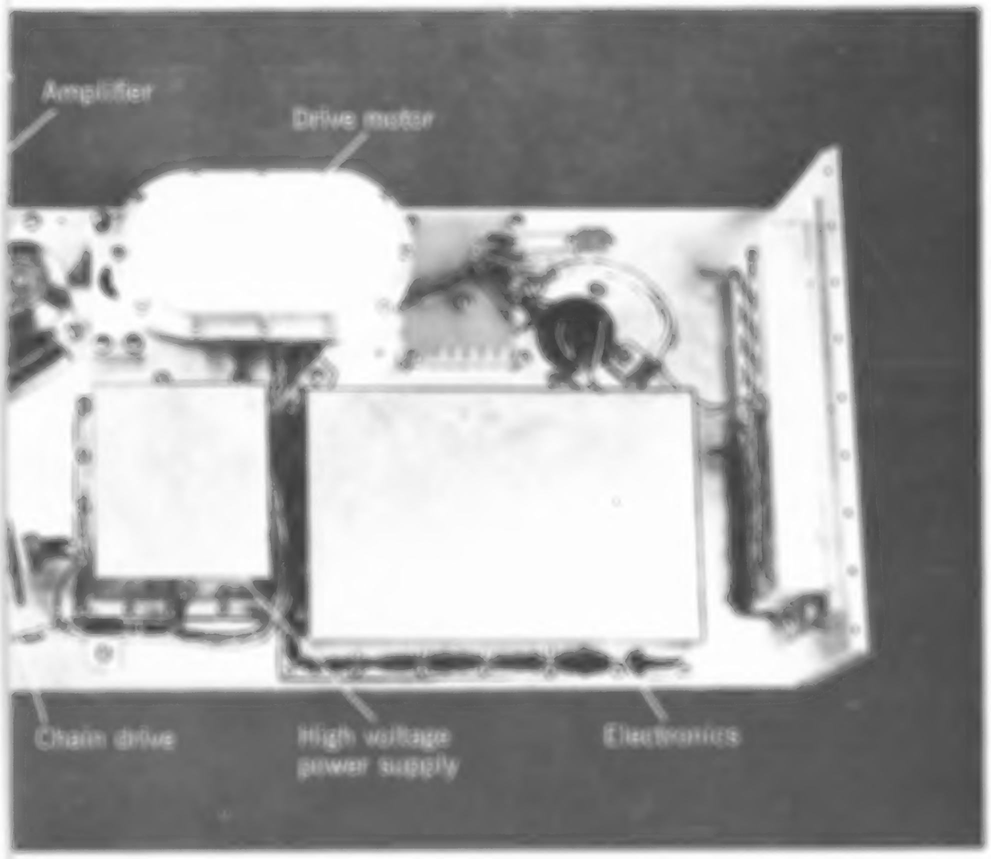
9

Many of the instruments just listed are inherently digital; that is, they count events and other discrete phenomena. For example, the number of Geiger counter discharges per second is an integer; the output of this experiment is already digitized. Housekeeping instruments that indicate switch positions are already digitized, because on and off modes can be described as 1s and 0s. Commands to spacecraft are normally digitized. First, a command must contain an address that picks out the desired satellite from the hundreds in orbit. The address will also have to select the specific part of the satellite that is being commanded. A command's address is similar to a telephone number; and it is digital. The second part of a command gives the order to the addressed piece of equipment. The order might be "turn yourself off" or "read out the tape recorder." These are switching commands that are inherently digital.

Other spacecraft instruments generate analog or continuously varying data. Suppose that the output


1 1 0 1 1 1 0 0 1 1 1 0 1 0 1 1
Satellite address 110 = 6
Satellite component address 1110 = 14
Instruction 011101011 = 235

10

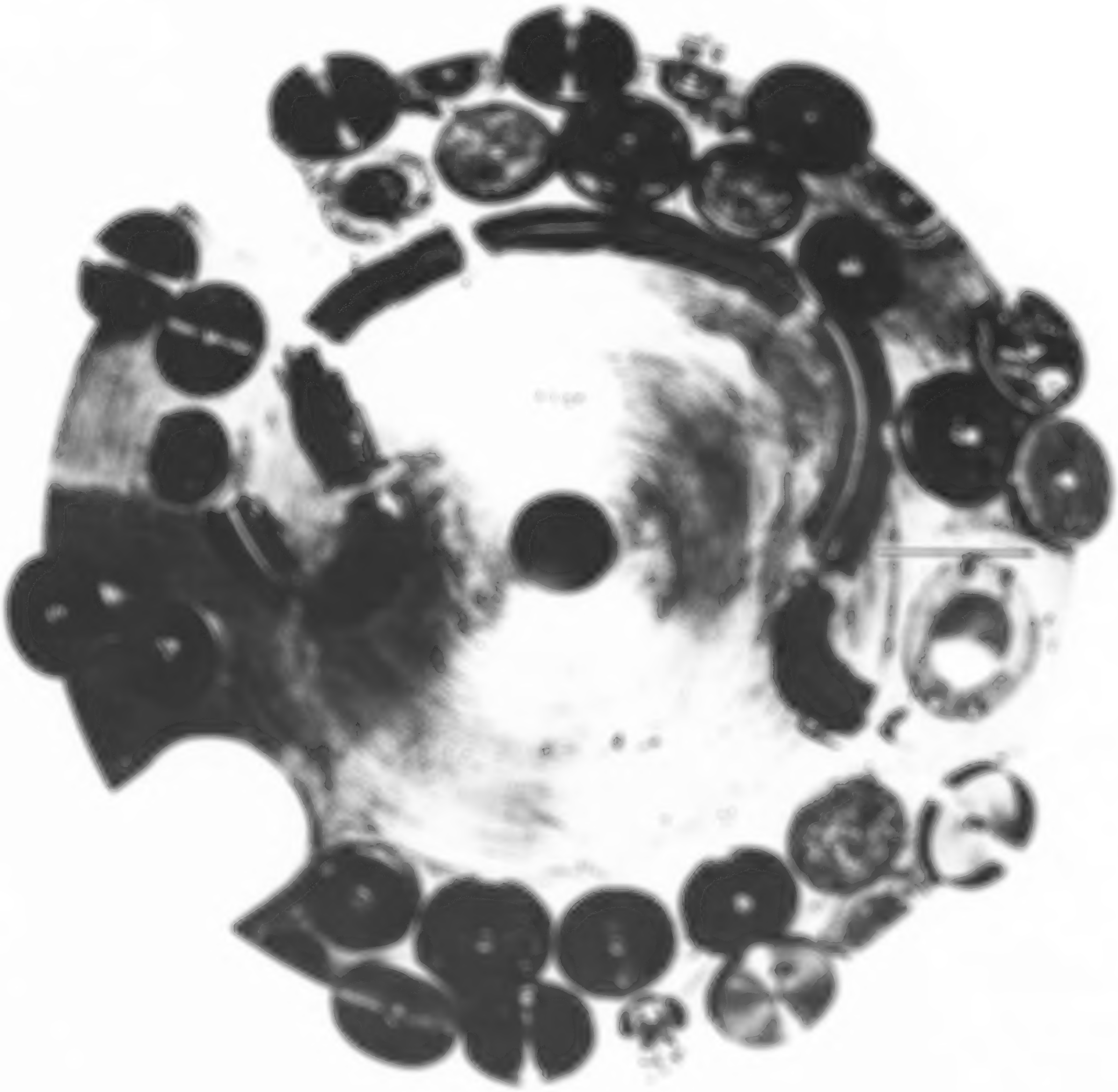


voltage of an instrument varies continuously between 0 and 8 volts (see illustration). This smoothly varying signal can be approximated by reading the instrument once each second and expressing the reading as a 3-bit word. If more precision is desired, a 4-bit word can be substituted. In this way, all analog signals can be digitized and made compatible with the popular digital codes, such as PCM.

Before the data from the various spacecraft instruments can be sent to Earth, they have to be organized into a *format*, a pattern that terrestrial data processing equipment can recognize. As the spacecraft communication equipment scans all the instruments, it assembles the readings into a data frame, which is like a movie film frame in that it is a snapshot of all spacecraft instruments at a specific time. There may be twenty words from twenty sensors in the data frame; all arranged in a specific order. For the sake of the sanity of the computer that will eventually digest millions of these data frames, the words are usually made the same length. The word length and the arrangement of words in the data frame make up the format of the data. In a sense, each spacecraft instrument communicates in a rather stilted machine language and then only when called upon.

Not all space data are so rigidly and thoroughly mechanized. The voice link connecting astronauts with the Earth-based mission controller will usually be analog; that is, the amplitude and pitch of the astronauts' voices will be represented by a continuously varying signal. Television pictures from NASA's weather satellites and planetary probes are often digitized, although they may also be analog in character, like home TV. In general, though, NASA leans toward mechanizing and digitizing its space data systems.

11 *Circular film packs are often mounted on recoverable satellites in order to obtain tracks of ionizing particles at high altitudes.*



Downlink From Space To Earth

So far, the assumption has been that radio waves would carry the torrent of spacecraft data downlink to data acquisition stations on the Earth. There is another way to gather data from space and the technique is superior to radio in several ways. All one has to do is bring the spacecraft back to Earth and examine what it has recorded. Data from recoverable spacecraft will not be real time data, but this fact is not always critical; in fact, delays are sometimes desirable.

Many of the experiments flown on NASA's Biosatellites must be returned to Earth for detailed study in the laboratory. In some Biosatellite experiments, scientists wish to determine the long-term effects of weightlessness upon specimens placed in orbit. The effects of space radiation may show up weeks later in subsequent generations of insects descended from satellite-traveling ancestors. Satellite film is far superior to television cameras in color rendition and detail. The spectacular colored pictures taken of the Earth by Gemini astronauts prove this point.

Man himself is a recoverable instrument in a sense. A scientist-astronaut can perceive and interpret the unexpected better than remotely controlled experiments. A geologist on the Moon, for example, could examine and collect samples of lunar rocks, explore craters, and track down clues to the Moon's origin better than a machine.

Man, for all his powers of observation and ability to adapt to the unexpected, is expensive to sustain in space. Machines make the more routine measurements for him by proxy, just as unmanned weather stations do here on Earth. Indeed, for the great bulk of space research, automated, unmanned spacecraft make the best instrument carriers.

Radio waves represent the only practical way to get the automated spacecraft's instrument readings back to Earth at present. NASA, however, is developing the laser as a communication tool. With the advent of high power lasers and techniques for modulating their thin light beams, engineers have carried out successful short range communication tests on Earth. In theory, lasers can carry considerably more information per second than a radio carrier; primarily because much wider bandwidths are available at the high frequencies generated by lasers. The major problems encountered with laser communication are:
(1) Aiming the thin beams precisely at the receiver, and
(2) The attenuation of light in the atmosphere.

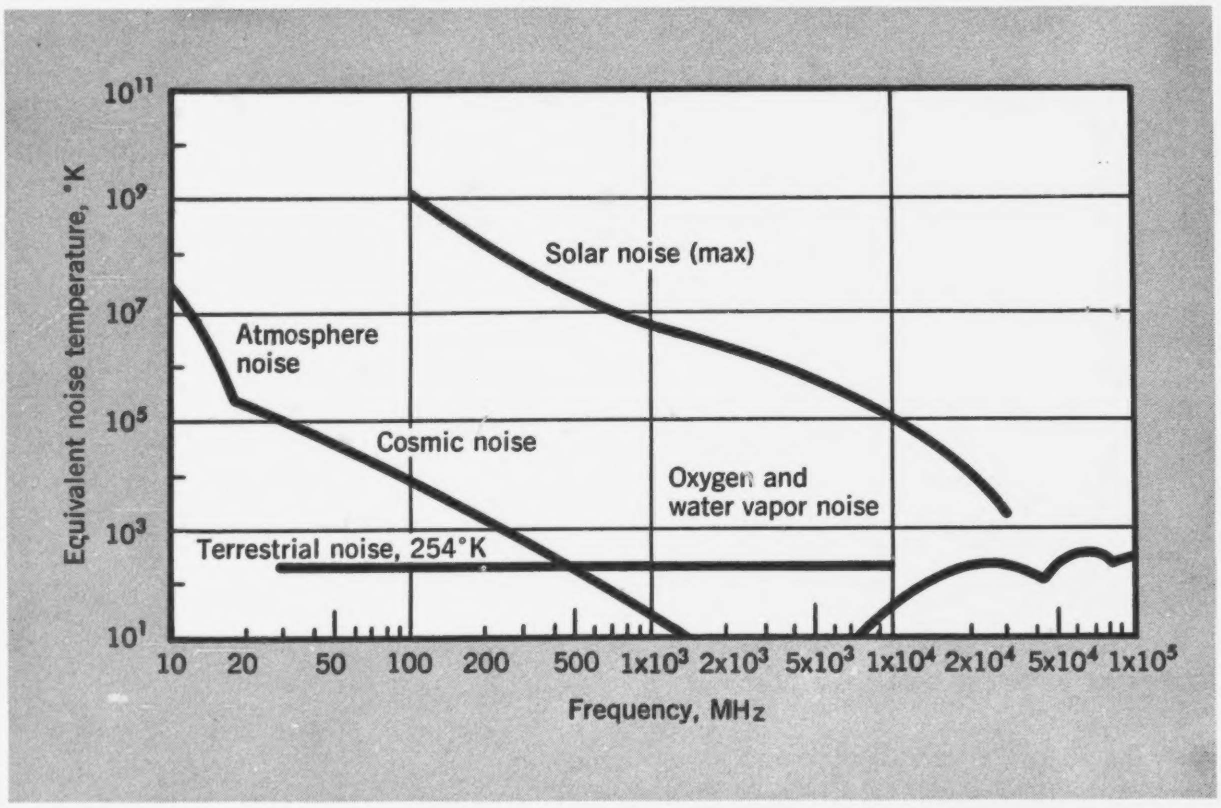
High transmitter power, big antennas, light weight equipment, high reliability; all are key factors in a successful space data system. Unhappily, we cannot have all of these desirables at the same time—compromises are necessary. One area of compromise comes when the carrier frequency is selected.

In choosing the carrier frequency, one looks first for a radio window in the atmosphere; a frequency band where atmospheric absorption is small. A broad radio window occupies the spectrum from 100 MHz to 10 GHz.* The low-frequency edge of this window is created by the Earth's ionosphere which reflects all radio waves below 10 MHz and seriously interferes with transmissions between 10 MHz and 30 MHz at times. The window's upper edge owes its origin to the atoms and molecules in the atmosphere that soak up the radio waves at these higher frequencies. To some degree, the window can be widened at its upper end by placing the terrestrial data acquisition stations in high, arid spots where the attenuation due to water vapor is reduced.

**1 MHz = 1 megahertz = 1,000,000 cycles/sec. 1 GHz = 1,000 MHz = 1 gigahertz.*

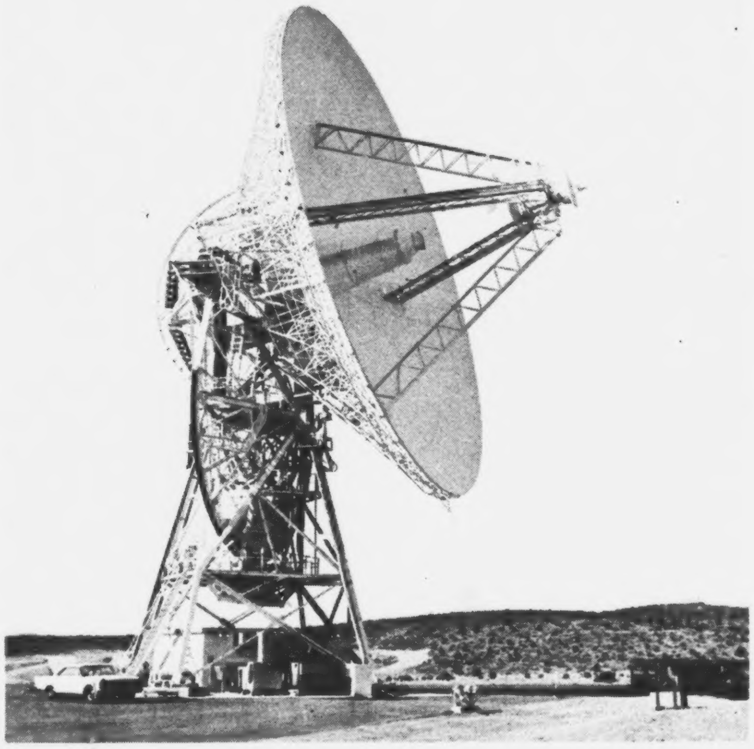
4

12 *Composite profile of noise seen by a receiving antenna.*



Next, noise sources must be avoided. Locating the receiving stations away from urban areas helps, but not all radio noise originates in man's cities. Under 20 MHz, the radio spectrum is burdened with radio noise created by lightning flashes and other atmospheric electrical activity. From 20 to 100 MHz, cosmic radio noise from outside the solar system poses a serious problem. There are many radio stars in the sky, and, of course, our own Sun is a prodigious radio source. Even the Earth, by virtue of its temperature, emits radio noise. A nearby hill caught in a station's antenna pattern introduces radio noise. Above 10,000 MHz, radio noise comes from oscillating oxygen and water molecules in the Earth's atmosphere; each molecule acts like a miniature transmitting antenna. Note that the low-noise region occurs just where the radio transmission window is located: 100 to 10,000 MHz. This is fortunate. Although some cosmic radio noise can be heard in this region of the spectrum, it is the best choice for space communication.

The next hurdle for the data stream is man-made. The spacecraft transmitter must employ a frequency in one of the bands approved for space communication by the International Telecommunication Union. The radio spectrum is so crowded by commercial, amateur, and military stations that space engineers find themselves cramped into narrow frequency bands. Most NASA scientific satellites have transmitted in the 136 to 137 MHz band, but more recently there has been a trend to higher frequency bands where the spectrum is less crowded and where cosmic noise is less of a problem.



13 *A DSN 85-foot paraboloid at Goldstone.*

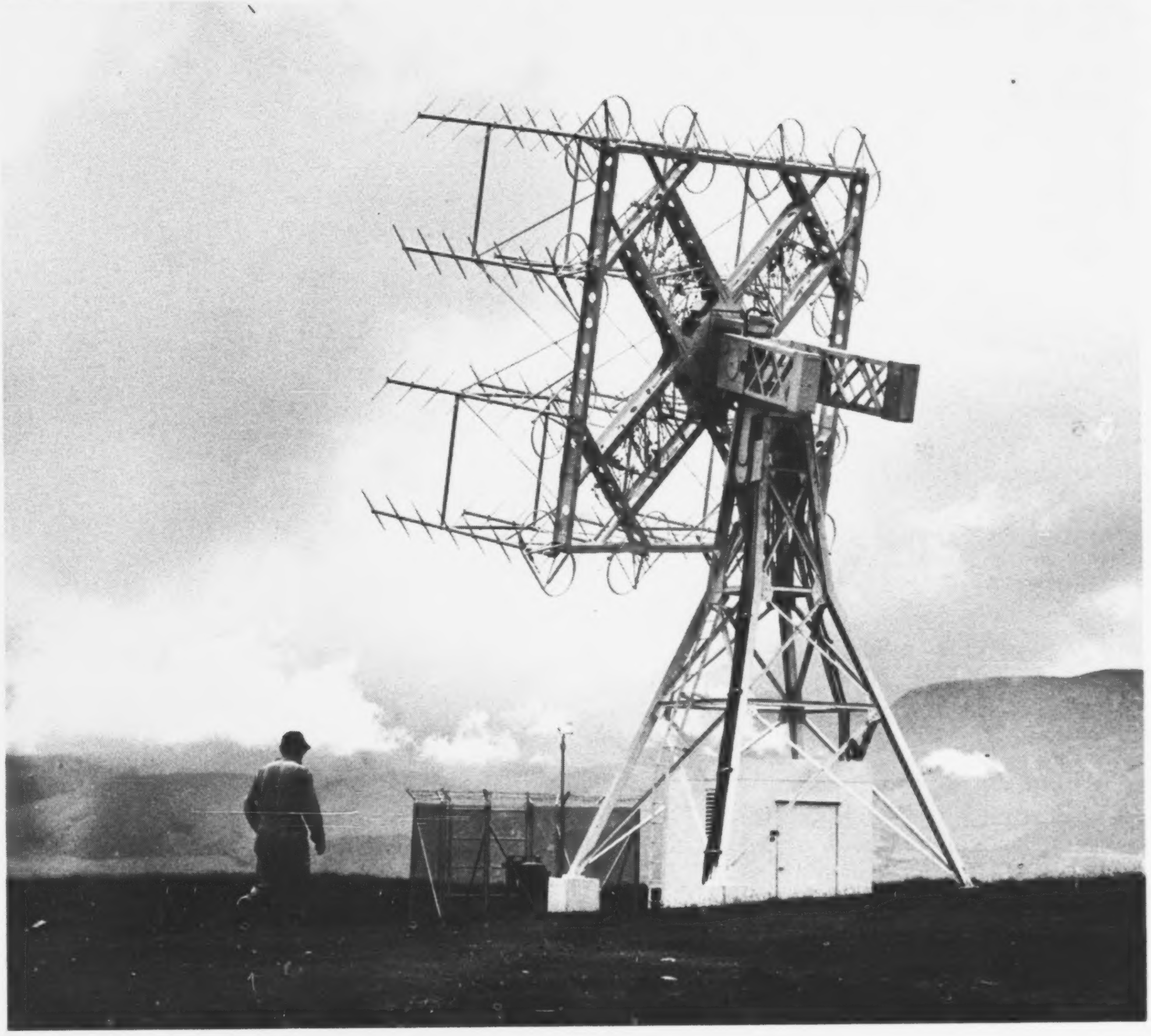
Data Acquisition

Working a spacecraft begins with finding it and then locking the station's receiving antennas on it so they will follow it automatically for the time it is above the horizon. This process is termed spacecraft acquisition. In 1958 and 1959, spacecraft were elusive because they were small and carried weak transmitters; they could easily get lost in the immensity of the sky. Unless a station operator knew exactly where to point his antennas he might never find the spacecraft. Today, the station operator has to select the right satellite from among the hundreds that pass over his site every day.

Suppose that a ground station wishes to work satellite X. A satellite ephemeris—a publication that does for a space tracker what an almanac does for a navigator—will predict when and where the satellite will be. NASA generates such data for its tracking stations from computer orbit analysis. When satellite X is expected on the horizon, tracking and radio receiving antennas are pointed in the direction predicted by the ephemeris. If all is well, the satellite's radio beacon will be detected by the tracking antenna. The tracking antenna will then automatically follow the satellite beacon signal, and the receiving antennas will be slaved to the tracking antenna; that is, they will be driven by motors so that they point in the same direction. Once satellite X is well above the horizon, a command is sent from Earth to read out the contents of its tape recorder. The data it has collected since it was last worked is transmitted (dumped) into the data acquisition antennas waiting below. One of NASA's large observatory-class scientific satellites may transmit several novels' worth of data—millions of bits—in a few minutes.

Acquiring data from a planetary probe is somewhat different. A probe far out in space is always in view for one of NASA's Deep Space Network stations. Seemingly, there is no need for a tape recorder aboard the spacecraft; no need for burst transmissions. In fact, the bit rates, as measured in bits per second, are so low that the probe must transmit continuously to utilize the data-gathering capabilities of its instruments. During planetary encounter, however, several new instruments (cameras, radiometers, etc.) will be turned on to scan the planetary disk. The flood of new data would more than saturate the probe's communication subsystem, so the data are recorded on tape and

14 *An automatic-tracking telemetry antenna used at STADAN sites to work satellites. Each of the sixteen rods is a "Yagi" antenna.*



played back slowly after the planet recedes in the wake of the spacecraft.

NASA has built three separate but mutually supporting worldwide networks of stations for tracking and conversing with spacecraft.

STADAN, the Space Tracking and Data Acquisition Network, is used primarily for working unmanned satellites, particularly NASA's many scientific and applications satellites.

MSFN, the Manned Space Flight Network, is applied almost exclusively to tracking and communicating with manned spacecraft, such as the Gemini and Apollo craft. The major stations are concentrated in a belt 40° north and south of the equator.

DSN, the Deep Space Network, is employed in tracking lunar, planetary, and deep space probes (the Surveyors, Mariners, Pioneers, etc.). It also augments the MSFN during the Apollo lunar flights. The DSN stations are spaced around the world so that they will always have all probes in sight.

The major external feature of any tracking and data acquisition station is its complement of large antennas. In STADAN, the smaller satellites are worked by arrays of "yagi" antennas while the bigger, high data rate, observatory-class satellites dump their data into 40 and 85-foot diameter paraboloidal antennas. The MSFN also employs small antenna arrays for listening to the manned satellites. For manned lunar missions, however, the MSFN has added several 30 and 85-foot paraboloids to some of its stations to ensure receiving the weaker signals from the more distant spacecraft. The MSFN 85-foot dishes are located adjacent to like-sized DSN antennas to assure uninterrupted communications and tracking during the critical Apollo lunar operations. The MSFN and DSN paraboloids track as well as communicate, while those assigned to STADAN do not track. The DSN also boasts a 210-foot diameter paraboloid at its Goldstone, California, station for receiving data from distant space probes. This antenna has picked up data from probes over 200 million miles away.

The big antennas are like the tops of icebergs—obvious, but suggestive of much more below the surface. Hidden within the station buildings are great quantities of electronic gear: receivers, transmitters, recording equipment, computers, power supplies, etc. This hardware is necessary to amplify the feeble signals received from the spacecraft and translate them into forms that can be readily transmitted to the network's control center. A network's stations are only temporary stopping points for the streams of data emanating from the several dozen spacecraft that NASA may be working at any one time.

The largest fraction of NASA's data originates on the numerous scientific satellites. Scientific data are usually not needed immediately—realtime transmission via NASCOM, NASA's terrestrial communication network, is unnecessary. Instead, most scientific data are recorded on magnetic tapes, which are then mailed back to Goddard Space Flight Center, Greenbelt, Maryland. Several score miles of magnetic tape are filled each day, depending upon the number of satellites being worked.

Critical, real time data flows through a data acquisition station in only a fraction of a second. Astronaut transmissions and important housekeeping data are amplified and fed into NASCOM's terrestrial communication lines without holdup except for the time it takes electrical circuits to act. NASCOM lines also carry commands from the network control centers to the station working the addressed satellite, thence to the satellite uplink by radio. Tracking data also flow to control center computers on NASCOM circuits. The computers return pointing commands to the next network stations so that they can more easily acquire the spacecraft when their turns come.

One other kind of communication traffic is especially interesting. It is employed primarily by the MSFN, where actual missions are months sometimes years apart. To maintain the MSFN in a high state of readiness, train operators, and check out equipment, network simulations are conducted via NASCOM. During a simulation, signals resembling those occurring during a real mission are sent out over NASCOM to the stations and MSFN control center. The signals simulate equipment failures, human mistakes, and anything else that might go wrong—or right—during a real manned flight. The simulations exercise the network and reveal weak points in human and machine.

Let us take a closer look at NASCOM. It is a global, realtime terrestrial communication network. Signals received from a satellite over Australia cross the Pacific and the U.S. mainland, arriving at Goddard Space Flight Center in less than a second. Goddard is the hub of NASCOM. Most network communications pass through the switching circuits there. In essence, Goddard is the equivalent of a telephone exchange, routing data and voice messages to the proper stations in all of NASA's three networks.

Goddard is aided by numerous relay points plus major overseas switching centers at London and Honolulu. Switching subcenters are located at Madrid and Canberra. All told, well over 100,000 miles of communication lines, undersea cables, and microwave links tie NASA stations together. During the Apollo mission, communication satellites add more circuits to NASCOM for wider geographic coverage.

Some of the points serviced by NASCOM are not network stations; for example, NASA's Ames

Research Center and Marshall Space Flight Center. Some points, such as NORAD and Spacetrack, are not even NASA facilities. Through these points, NASA exchanges tracking data and other information with other governmental agencies. NASCOM is, in fact, an important national resource. As such, it is integrated into a much larger worldwide network called the National Communications System (NCS). NASCOM helps "wire the world" for U.S. government communications.

Where The Brains Are

Each of NASA's networks has its own control center where mission decisions are made. As fast as real time data reach Goddard Space Flight Center on NASCOM lines, they are switched on to circuits leading to the appropriate control centers. These are:

For STADAN: Mission Control Center, Goddard Space Flight Center, Greenbelt, Maryland

For the MSFN: Mission Control Center, Manned Spacecraft Center, Houston, Texas

For the DSN: Space Flight Operations Facility, Jet Propulsion Laboratory, Pasadena, California.

NASCOM might be called the nervous system of these man-machine complexes that join a spacecraft at one end and man at the other. The control centers, which obviously include man, are the brains and decision makers.

In the human body, the functions of the brain include perception, evaluation, decision-making and the dispatch of commands to the appropriate parts of the body. NASA's control centers do the same. Conceivably, a NASA network could run itself without the services of man. A big computer could make all of the decisions if all answers to potential questions were stored in it before the mission. Unfortunately, we do not know all of the questions prior to a mission. Almost all spacecraft missions have presented unexpected situations with which only man, with his unique creative capabilities, could cope. Man has to be in the loop—as control engineers say—because space exploration is not routine.

15 *The Mission Operations Control Room of the Mission Control Center at Houston. The consoles and displays suggest the magnitude of ground support necessary for a manned mission.*

Even though man is in the loop, big computers are needed to control NASA's spacecraft. A computer takes raw tracking data from NASCOM lines and translates them into orbital parameters for the mission controllers. A computer also translates the long strings of pulses representing housekeeping data from the spacecraft back into human language; not necessarily English, more likely some sort of visual *display*. A typical visual display for a manned satellite mission portrays the spacecraft position at all times on a world map.

A computer also helps man cope with the flood of space data by flagging data that deviate too far from normal. The flag may be a red light on an electronic console in the control center. To illustrate, if the spacecraft power supply voltage drops below a specified level, on goes a red light. The human operator then makes a decision and takes action.

Sometimes man may be completely bypassed by his machines. For example, the atmosphere and temperature of a manned spacecraft cabin may be maintained by decision-making machines, just as a home thermostat turns on the furnace when it is needed. Another illustration: during the launch of a large rocket, computers monitor and evaluate engine pressures, temperatures, and fuel flows. They can evaluate much more data than man during this short but very critical period. Things may happen so fast that only a computer can make decisions fast enough to prevent a disaster, say, by shutting off the engine.

Suppose that a manned satellite has just fired its retrorocket and is curving down for a splashdown in

16 *Real time computer complex at the Goddard Space Flight Center. Manned orbital and lunar flights are supported by this equipment.*

the Atlantic. Just where will it hit? A man could work through the mathematics using data from the MSFN tracking radars, but it would take far too long. The computer comes to his aid by predicting the splashdown point and by displaying this information visually on a screen for the mission controller.

Summarizing, man's machine partner can make routine and certain emergency decisions by itself. Where man must be in the loop, the machine translates data into terms he can understand readily and then displays them for him. Further, a computer can predict consequences of potential actions. Man is reserved for creative decisions—a function in which he surpasses the machine.

Data Processing And Archiving

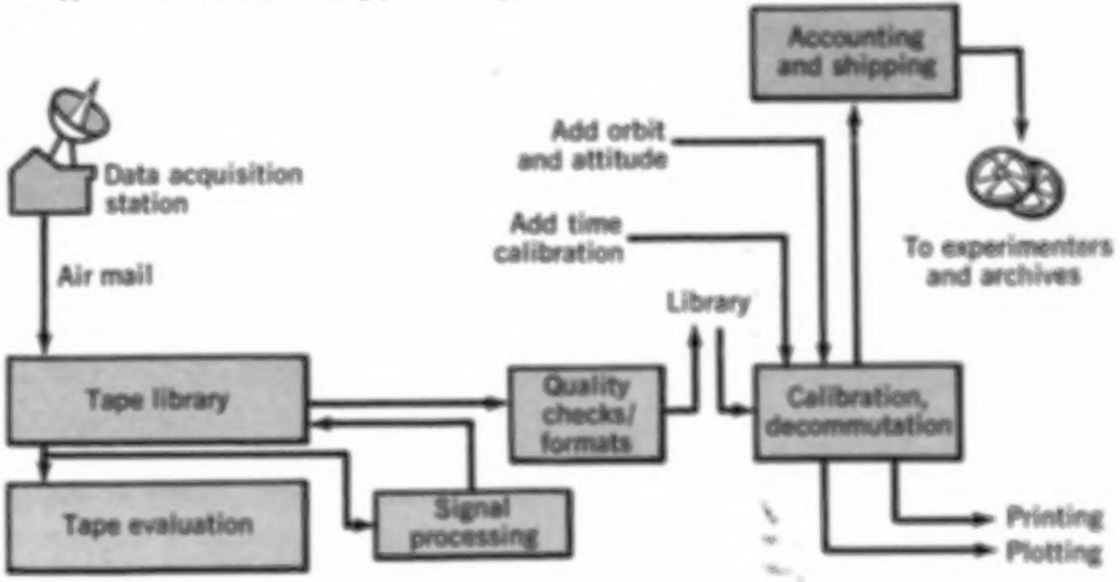
Spacecraft, especially the scientific satellites, are so prolific as data gatherers that it is hard to describe the data deluge in easily comprehended terms. To say that an observatory-class satellite may dump 100 billion data points into STADAN antennas during its lifetime gives little physical feel for the situation. Equating 100 billion data points to a half million library books is a graspable statistic. Few libraries have this many volumes on their shelves. Add to sheer quantity the things that NASA has to do to each data point and you will understand why the processing of space data is a job for big computers.

NASA has evolved procedures for turning the data flood into a well-organized stream of information that is highly useful to space scientists. Each datum arriving at Goddard Space Flight Center from a scientific satellite is edited, cataloged, indexed, and archived. All NASA-produced data are retrievable upon demand from the thousands of reels of magnetic tape stored at NASA tape libraries. Also processed are the data generated by NASA weather satellites.

In practice, data handling is not so formal and formidable. Satellite and probe experiments are usually built by individual scientists and groups of scientists. As the reels of magnetic tape pass through Goddard's data processing lines, a computer sorts out each scientist's data and, if he so desires, edits and partially digests it for him. A scientist with an experiment on one of Goddard's satellites can get his data quickly and tailored to his needs. The data must, however, be preserved in NASA's data archives for future reference.

Upon opening a magnetic tape mailing carton, we find a half-inch-wide tape filled with data in the form of tiny magnetized spots. A tape from a STADAN station will contain data from the scientific experiments on the satellite being worked by the station when the tape was made, plus housekeeping data that tell the scientist which way the satellite was pointing when the data were taken. The STADAN station will also add time signals and other reference data that help the scientist interpret his data. Usually, the data on STADAN tapes are still multiplexed and must be decommutated; that is, sorted out experiment by experiment. Different satellites employ different modulation schemes and

17 *Typical flow of data during processing.*



different data formats. Goddard has built data processing lines, similar to industrial production lines, that make order from the diversity of the data collected by STADAN stations.

At Goddard, a facility called STARS (Satellite Telemetry Automatic Reduction System) digests magnetic tapes and begins the task of data organization and processing. First, the taped data are decommutated and, if they are still in analog form, digitized. STARS computers can often recognize and flag errors that may have crept into the data; some telemetry codes (notably PCM) have self-checking features. The STARS production line also adds universal time to the data points. Satellite position and orientation are inserted where needed. The products are termed *experimenter tapes*. If the scientist desires, his tapes can be processed further. The computer will draw graphs, tabulate data, and even direct the scientist's attention to particularly interesting developments.

Several data processing lines are always in operation at Goddard and the other spacecraft control centers. There is a steady flow of edited, processed, indexed tapes to data libraries, where they will be available to anyone who may wish to see them ten or twenty years hence. To illustrate the potential of such scientific data, old astronomical photographic plates have proven immensely valuable in checking to see if a newly discovered comet was ever recorded before, or if the spot where a nova now flames was occupied before.

Archiving infers long-term data storage. NASA has created the Space Science Data Center at Goddard Space Flight Center for this purpose. The Center is responsible for storing, retrieving, and disseminating NASA's space data. On the international level, World Data Centers have been established in Washington, Moscow, and other locations. All countries send copies of their important space data to the World Centers, where they are indexed and stored for future use.

The data archives represent the terrestrial end of the link tieing spacecraft sensors to man. The link may be only a few score miles long in the case of sounding rockets, but it stretches across the solar system for deep space probes. For the first time, man has extended himself beyond the Earth's atmosphere into outer space. For the first time, he is seeing, touching, and directly measuring the cosmos. Without radio communication, computers, data acquisition antennas, and the rest of the space data system, this would be impossible.

VI

America
In
Space:
The
First
Decade

Linking Man and Spacecraft

National Aeronautics and Space Administration